PRECISION INVESTMENT CASTINGS

by

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Introduction

Precision investment casting could be profitable as an industrial process in at least 25,000 metal products plants, foundries and machine shops. As a source of supply on contract basis this process also could be highly useful to at least 100,000 manufacturers and products distributors who would buy from the casting houses.

Precision investment casting is a method for making parts and semifinished or even entirely finished products of unusually economical qualities. It is a resource for the toolroom. It can originate raw materials for fabricating by machining and other processes.

Several new processes are developing rapidly to increase the values of all alloy materials and methods without in any way reducing the values of the older processes. Modern developments of the use of the salt bath, modern welding, induction heating, powder metallurgy, electronic controls and ultrasonics are among them. All of these processes have much to gain from each other. All are built on the older processes, the punch press, the mechanized forging equipment, the turret lathe, the sand-casting foundry, as foundations.

As one of the newest processes, precision investment casting is now being asked to do impossibilities merely because impossibilities seem so reasonable to those who have casually read about it, and is being refused opportunities to make use of its full abilities merely because those abilities seem so incredible.

All new processes must go through that stage, and all older ones remain in it to some extent. But the more its "misunderstood" stage can be shortened, the sooner a process can begin to contribute its full value to industry. Shortening that stage for precision investment casting is the objective of this book.

How This Book Is Organized. Every engineer who has developed a product design and then worked out a production sequence for it knows that a schematic design has to be made first and then a general scheme of production, after which the entire sequence is checked back and forth until the plan is smooth. A difficulty at step number ten requires a change at step number two, and a high cost at step fourteen necessitates a modification of the entire design.

If the production process is widely familiar, as would be the case with automatic screw machine operation, the best way to organize a technical book regarding that process would be in neat compartments like a mail order catalog, so that the engineer could turn immediately to the pages he needed. But precision investment casting is far from being widely familiar to engineers. Therefore, a carefully calculated attempt has been made in this book to put each bit of information where the engineer will need to be considering it and thus to eliminate unnecessary checking back and forth in the smoothening of his designs and production plans.

The first few chapters should serve to tell the engineer what precision investment casting is, what it does, and how it does it. From these chapters he can make up his mind as to whether precision investment casting has anything to offer him or not, and whether it is a process which he should operate in his own shop or one for the products of which he should turn to outside suppliers.

Any plan to make use of a production process, and especially of a new process, requires a sharing of the burdens of analysis and of responsibility for results. The remaining chapters, therefore, go on to tell the engineer what must be done in product design and redesign in order to get the best results from precision investment casting, and how the process can be operated to obtain the desired ends. The resources and weaknesses of the process are described, the predictable lines of its future development are clearly indicated, and the practical methods by which the process may be operated on a sound basis are analyzed.

The need to put every bit of information at the "thinking point" where the engineer would take it up if he had operated this process for ten years, is enhanced by the diversity of precision investment casting methods. This process has wide selections of options at every procedural step. The intention of this book is to show the options at every step, but also to point out the limitations which each option imposes and how those limitations will affect other steps. In this way the engineer can eliminate from consideration for this process the product designs which are impractical to the process, and can apply precision investment casting to those designs and problems in which it will contribute its highest values.

Edwin Laird Cady

New York, N. Y.
January, 1948

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Chapter 1

Description and History

From the beginnings of the age of metals, men have made products of intricate shapes by melting the metals, pouring or "casting" them into specially prepared molds, and letting them cool and solidify to the general dimensions and shapes of the mold interiors.

The limitations of casting always have been those of precision. And to the engineer, "precision" usually connotes "repeated and exact duplication of desired results." A machine which can consistently duplicate the same high accuracies on the same dimensions of the same parts is a "precision" machine. By classic example, if a man makes one rifle and all of its parts are accurate, he has done an *accurate* job; but if with equally good design of all parts a factory produces several thousand rifles and all their parts are so alike and accurate as to be completely interchangeable, the factory has done a *precision* manufacturing job.

Anybody is free to romance and dream about the precision troubles of the early metal workers as they "cast their molten metals into the earth" in the same lingual sense that their farmer brothers were "casting their seed into the ground." Some of the castings certainly came out rough and pitted on their surfaces. Some experimenter must have tried pounding the surfaces of rough castings to see if he could smooth them, and someone probably found that this "working" strengthened the metal.

On the day that this work strengthening was recognized as a principle of precision, the battle of "intricacy *versus* simplicity" was well begun in the metals-working field. It is still going on.

Some castings were designed to have straight and flat surfaces which were easy to hammer. Other shapes were curved, difficult to hammer without pounding them out of shape, perhaps having some surface areas which the hammer could not reach at all. In the engineering sense, and from the viewpoint of the hammerer, any shape difficult to hammer was "intricate" and any easy to hammer was "simple." To the engineer the word "intricate" always has its true dictionary meanings of "perplexingly involved; complicated."

As seen by the caster, intricacy and simplicity were entirely different matters. Shapes so complex as to be almost impossible to hammer were simple to cast. True and parallel planes which were simplest to hammer could be "perplexingly involved" to cast because the mold shapes allowed for no pattern draft and the cavity walls were difficult to keep smooth. A product design, therefore, was intricate or simple depending upon the process by which the product was to be made and not solely upon the complexity of contours. It still is.

Knowledge that the shape of an object greatly affects its structural strength had been obtained long before the age of metals. It probably did not take many generations of metal-product designers to find out that objects closer to the desired contours and dimensions were more useful as tools and weapons. Accuracy thus entered the picture. And it must quickly have become clear that the higher the intricacy of a design the greater the difficulty of obtaining accuracy. Accurate control of surface finish also had been known before the age of metals. In metal products it was one of the most difficult accuracies to achieve.

The securing of greater strength by the alloying of metals, and the consequent reducing of some problems of intricacy, came on in due course. Men learned how to heat-treat metals for still greater strength.

In the days when hammer forging plus heat-treating between hammerings were just about the only secondary operations performed on castings, the product designer had to respect the fact that what was intricate in shape for forging was simple for casting, and he had to choose whether to put the burden of intricacy on the casting or on the forging or to divide it between the two operations. Often he made compromises, sacrificed some of the advantages of casting to gain those of forging, or the reverse. He still does. He did not like those compromises then. He does not like them now.

Many of the compromises were made to gain precision in repetitive operations. Folklore is full of tales of "magic swords" which, by sheer accident, turned out to be better than other swords of exactly the same dimensions. The boasted short swords of the Romans were short merely because craftsmen could not turn out dependable longer ones with precision and therefore compromised on the shorter ones.

As production processes multiplied and men became masters of them, the situation increased in complexity but did not change in nature. At present, what is intricate to a lathe is simple to a milling machine (and the reverse); what is intricate to a punch press is simple to a die casting machine; and what is intricate to any single machine can be simple to a sequence of different machines and processes. The designer selects his processes, makes his design compromises, tries to line up sequences of processes which will eliminate the need for compromises.

The masters of each process try to have all designs made suitable for their methods, just as they always have done. The "battle of the processes" for the right to dominate the making and therefore the designing of specific metal products never ceases; it merely increases in complexity and ramifications. And with every new development the designer has just that many more chances to eliminate compromises, and to make them.

Every new process (if there *are* any new ones) and every improvement of an old one brings new chances to achieve precision in spite of intricacy. There now are so many variants that the very word "precision" has almost no meaning unless applied to one or more specific factors. Precision always can take several forms and always is a matter of degree. Examples: "precision tolerances" or the repeated and duplicated holding of exact dimensions; "precision metallurgy" or the repeated obtaining of specific chemical and physical conditions of metals and alloys.

Very early in metal-working practices it was learned that metals cast into some kinds of earth came out much better than those cast into others. This selecting of earths was one of the first steps toward production control, toward precision manufacturing. Later on the special earths or sands were so carefully selected and processed and molded that they became known as clothing for the castings. In old time English any specially prepared clothing, such as a uniform, was known as an "investment"; we still use the expression "invest with the robes of office." Therefore any specially prepared mold for casting, whether the mold is made of sand or ceramics or anything else, is an investment. And to the extent that any investment promotes duplication of desired results, it is a precision investment.

Every type of investment for every technique of casting is improving in precision. The improvements must follow definite paths, achieve definite properties of precision.

Precision Properties of Investments

A precision investment is itself a product of precision selecting, mixing and processing of ingredients. It is a precision tool to the extent that it always will perform in the same desired way if always subjected to the same conditions.

An investment always is a tool. Its precision is important only in what it can do as a tool for the casting process. There are several ways in which it can contribute; several forms of precision which an investment can have in varying degrees. The ones most useful to the product designer are described as follows:

(1) **Ability to Provide Cavities of Intricate Contours.** The word "intricate," as has been explained, has no engineering meaning except in relation to the tools and processes by which a product is to be made.

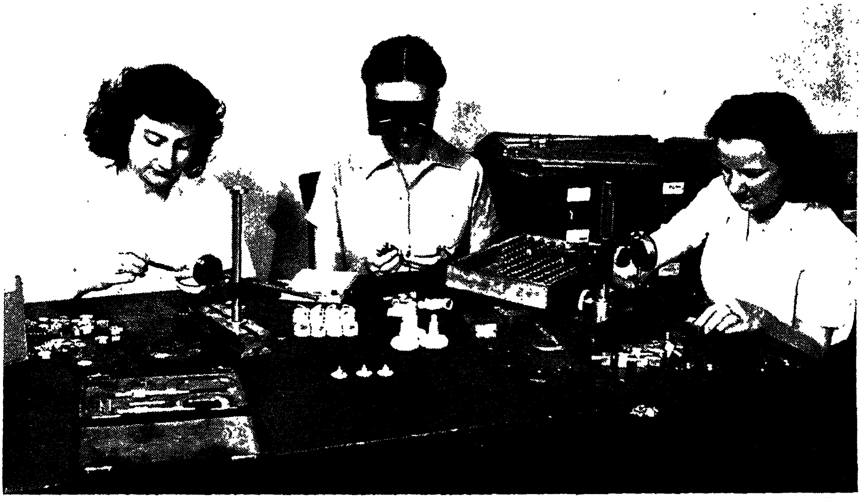
All investments, and therefore all casting processes, find it simple to produce curved and irregular and otherwise involved *exterior* contours which are highly intricate for other processes. But when a pattern has to be pulled or "drafted" out of the investment, the "first law of physics" operates to limit the exterior contours of that pattern and therefore of the casting. This law states that one solid body cannot be passed through another without deforming either. The pattern can have no contours which cannot be pulled free without rupturing the investment. And there are limitations upon the *interior* contours practical to cast when such patterns are used. Cores remove some of these interior limitations, and some of the exterior ones.

When means are found, as in permanent mold casting, plaster mold casting, die casting, and precision investment casting, to produce cavities in the investment without the need to withdraw any pattern, there are far fewer limitations upon the exterior and interior contours of those cavities. One investment, therefore, can be capable of kinds and degrees of precision impractical or even impossible to another. By selecting materials and methods for making an investment the precision of the casting process as compared to itself and to other production processes can be increased and the product designer can get rid of some of his intricacy *versus* simplicity compromises.

(2) **Ability to Hold Exact Dimensions.** Every kind of investment has limitations upon the accuracies within which the dimensions of its cavities can be held. This is especially true if the ac-

curacies are to be readily obtained at commercially practical costs.

Some investments will shrink, swell or warp during the curing process that occurs between the forming of the cavities and the casting of the metal. Others, such as sand molds, are molded in two or more segments which must be fitted together to form the final mold, causing some losses of accuracy with this fitting process. Obviously, the accuracy of the final casting can be no greater than that of the mold into which the metal is cast.



(Courtesy Whip-Mix Co., Louisville, Ky.)

FIGURE 1. Casting dimensions can be so precise that precision instruments are needed for checking them.

(3) **Ability to Withstand the Forces of Casting.** Molten metal exerts force against the walls and structures of the investment as it is poured into the cavities. If some highly liquid and free-flowing melt such as gray iron is to be poured by gravity, the investment does not need much structural strength. But if the metal is not free-flowing, or tends to have an erosive action on the sides of the mold cavities, or is to be injected at high speed or at high pressure, the investment needs enough structural strength to maintain the dimensions and contours of its cavities under these conditions.

Structural strength in an investment is a matter of outright physical strength of the investment material, and of the contours of the weakest parts of the investments. Product designs can require mold cavities to have cores and other projecting parts which are so long and thin and little supported that even though the most fluid of metals be poured, only the strongest of investment materials will stand up.

The more the product designer can rely upon the strength of the investment material as a material, and the less therefore he has to rely upon structural design within the cavities to provide the necessary strength, the wider is the list of features and the variety of contours which he can incorporate in products which are to be produced by casting. Physical strength in an investment adds to the designer's ability to overcome intricacy while achieving precision.

(4) **Ability to Be Fitted to Metallurgical Needs.** Some metals need to be cast into extremely hot investments, some into cold ones; with others the investment temperature makes little difference. There are alloys which can be cast only in partial vacuums, alloys which must be melted and cast only within controlled atmospheres such as nitrogen or other inert gases. The atmosphere may need to impart additional carbon or other materials to the surface of the casting, or may merely need to avoid the removal of any carbon (decarburization).

In some cases the investment must be completely dry, in others slight dampness is permissible or even beneficial. The alloy may need the investment to be a good heat insulator so the cooling of the casting is slow and even. Another alloy may need a good heat-conducting investment so that the exterior of the casting cools and solidifies while the interior is still liquid or plastic, or so that the entire casting with its investment can be quenched to harden the metal.

Some investments must have separate areas of differing thermal conductivities; a rapidly conducting area can produce a chilled or hardened area on some alloys, a slowly conducting area a softened and highly machinable one.

The same alloy may need one condition of the investment if cast into one shape, another if cast into another. Thin sections of castings, for example, may need entirely different properties in investments than thick ones.

The chemistry of the alloy is important. A sulfur-bearing investment material which is excellent for some nonferrous metals can be ruinous to ferrous ones.

Every time an investment is found to have new abilities to be tailored to the needs of the metallurgist the practical application of metallurgical science takes another step forward.

(5) **Ability to Provide the Desired Surface Finishes.** For thousands of years it was taken for granted that the surface of nearly every casting would have to be cleaned up or removed by abrasive blasting, filing, chemicals or by brushing or rubbing before the casting could be used or could be subjected to machining, forging or any other secondary operations. This was one of the reasons why high dimensional accuracies so seldom were attempted in casting. It was easier to achieve accuracies while treating the surfaces and by secondary operations which removed still more of the "skins" of the castings than by casting accurately.

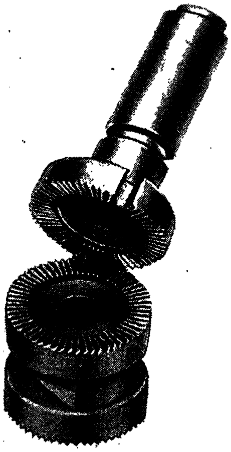


FIGURE 2. Surfaces can be so high in precision as to need no finishing for the function of the product.

(Courtesy Arwood Precision Casting Corp., Brooklyn, N. Y.)

Modern investments which fit the needs of the metals can produce surfaces which need little or no cleaning up. In this way they can reduce design and production costs, and increase the utilities and salabilities of products.

(6) **Ability to Be Removed at Reasonable Cost.** The cost, including original costs for mechanical tools and equipment and for any necessary chemicals, to remove an investment from the finished castings without marring or damaging the castings, can be an important part of the costs for a casting process.

The presence of sand or of other particles of investment materials mingled with the oxides or other unwanted chemical compounds on the surfaces of castings has been one of the main reasons why it so long has been taken for granted that the surfaces of castings must be removed or cleaned up before the castings could be used. An investment material, therefore, which has a tendency to embed itself in the surface of the casting, is a problem to the surface finish of the casting and to the accuracy of the casting process as well as a high-cost material to remove. And an embedded material can be highly abrasive and destructive to the metals-cutting tools used in machining away the castings surface and to the bearings and other working parts of machine tools.

Ability of the investment material to be removed affects the intricacy and the accuracy which the designer can expect of the casting process, and also affects the entire production-line costs of making products by the casting method.

(7) **Ability to Be Used at Low Cost.** If the cost to make and use an investment is too high for commercial practicability, that investment is a mere laboratory curiosity.

To the extent that the dies used in die casting and other permanent mold casting can be called investments, the repeated use of the same investments for large numbers of casting can cause the investment cost per casting to be low and thus justify high first costs. And investments molded of ceramics materials by ordinary molding methods and capable of repeated use without remolding are not unknown although they are uncommon. But most investments are destroyed in the process of casting or of removing the castings and must stand or fall on their costs for "one time" usage. Abilities of materials of which investments are made to be recovered or reused make only minor differences in final costs.

As the cost to make and use an investment goes up, the designer must find in it increased capabilities to solve problems of design intricacy, to suit the needs of metals, or otherwise to serve the needs of the kinds and degrees of precision he wants. The higher-cost investment may reduce the costs to finish or to machine the casting and so justify itself by reduced overall costs to make a product.

In investments as in any other precision tools, the higher the costs to make and use, the narrower the field of application.

The Precision Investment or Dispensable Pattern Process

Investments can have many combinations of properties. The investment which is best for one alloy may not be good for another. The investment which is best for one shape, or one surface finish, or one degree of accuracy, or one desired hardness or other physical condition of an alloy may be impractical for other products made of the same alloy.

Search for more kinds of investment materials having new combinations of properties and for new ways to mold materials into higher precision investments has gone on for centuries and probably will continue for hundreds of years more.

Somewhere along the line—it may have been in ancient Egypt or ancient China—someone hit upon the idea of making a wax replica of the item to be cast, surrounding this replica with a ceramic material, letting the material harden into an investment, melting and burning out the wax, and thus producing an investment having highly intricate and accurate cavities. The idea was to be rediscovered many times before the process achieved its present industrial status.

The dispensable pattern, which may be made of wax or of any other evacuable material, is the distinguishing characteristic of the *precision investment casting process.* And upon this fact hangs an engineering controversy regarding correctness of nomenclature.

There is no proof that investments made by this method exemplify any more "precision" than any others. It all depends upon what kinds and degrees of precision are wanted. Therefore, the argument runs, why not call the process "dispensable pattern casting" or "dispensable pattern investment casting," and have done with any possible confusion?

The name "precision investment casting" has been applied so universally to this process that in this book we must continue to use it. Nevertheless the dispensable pattern is the one feature which makes this casting process different from any other.

The dispensable patterns were hand made one-at-a-time for thousands of years. It was possible for a sculptor to make an original and full-sized model out of a material as easy to carve and to shape as wax, make all of his mistakes and changes on the model, then invest and evacuate the wax and cast a piece which needed only a little finishing. Benvenuto Cellini produced some of his masterpieces in this way. But while he and others achieved beauty and even accuracy by this method, they did not obtain the duplication of many pieces which would have made the process a precision one.

A few decades ago the dentists picked up the method as a way of making dentures. Soft wax was applied to the patient's mouth, the wax assumed the true contours which the dentures were to have, the wax pattern was invested and evacuated and true dentures were cast. This too was a one-model-at-a-time operation.

Then, in the early 1930's, the idea of making duplicate dispensable patterns so that many parts which were exactly alike could be cast, was developed. This was the beginning of precision investment casting as a true industrial precision process. Industrially, this process is new.

The duplicate dispensable pattern idea was simply a means for tooling-up for precision. Almost all modern production methods are very old processes tooled-up for precision or repetitive operation. The modernization of any process starts with the old "tricks of the trade" or, in more modern engineering language, the "know how," works out tooling which can apply that "know how" on a precision basis, acquires more "know how" through experience with the new tools, makes better tools in accordance with the newly acquired "know how," and goes on with further steps.

Improvements made by new tooling almost always are abrupt. Anyone who has studied the effects of the turret lathe on the production line and on product design, for example, and then has studied the effects of the automatic screw machine development, knows this to be true. Die casting, precision stamping, acetylene welding, arc welding, superfinishing, dozens of other processes all were abrupt in their effects.

The new tooling which almost overnight changed precision investment casting from a handicraft art to a true mass production process was one of the most abrupt developments in the history of industry. It has been followed by intensive research and wide experience to develop the process still further. The accumulated "know how" made possible the design and production of the airplane supercharger, of radar, and of hundreds of other devices which need highly intricate parts. And the full impact of this process upon industry has not even begun to be felt. There is no product of industry, no production equipment or method, which will not in some way be seriously affected by precision investment casting. This has been true of every important new process.

Operation of the Process

Precision investment casting requires eleven steps. These will be described in greater detail in subsequent chapters of this book. The functions of the various steps are presented here.

Step 1. Planning the Production Procedure. Precision investment casting is capable of many variations in its methods. The item which is to be cast, therefore, has to be studied carefully to determine exactly what methods and materials as well as tools should be used.

Shrinkages in the casting process, possible distortions in the casting process and in the patterns themselves must be studied. Quite often, experimental runs must be made on new products. And even after several production runs of an item have been made, improved methods still can be found.

Precision investment casting of some items can be done by anyone who has even a modicum of mechanical knowledge and skill. But this fact has been greatly overemphasized. Production of the items for which the process has its greatest value requires a high degree of engineering skill, plus knowledge of metallurgy, plus special experience in the process itself.

It is in this "planning of the job" stage of shop operation that most failures are made. The planning often has to go into changes of the product design in order to take full advantage of this process or to reduce costs without losing design values. Division must be made between the accuracies and contours which are to be achieved by casting and those to be had by machining or other methods. "Casting for the sake of casting" is all too common a mistake.

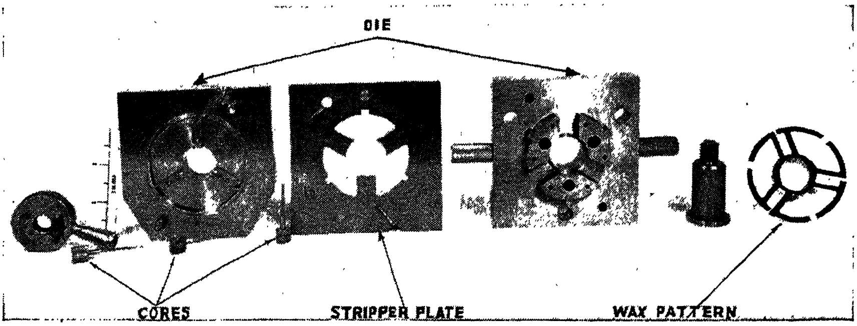
The cost of tooling must be kept appropriate to the values of the process and the sizes of production runs. Precision investment casting is not always a "low-cost tooling" process. Higher cost tooling can reduce costs and improve qualities in this process as in any other, but can fail to justify itself or can prove itself highly economical depending upon the same factors that govern tooling costs in all processes.

Step 2. Making the Patterns. Dispensable patterns are made of waxes, of plastics, of mixtures of the two, and of other evacuable materials, each of which has its advantages and disadvantages depending upon the size and weight and contours of the item to be made and upon other steps in the production sequence.

The dispensable patterns themselves are castings, or in rare cases are extrusions and in extremely rare instances are stampings or machinings. They must be cast into molds or investments of some kind, or by secondary modifications of the casting process they may receive forming operations performed by moving parts within dies. Preparation to make the dispensable patterns requires either the making of an original or "master pattern" or else the making of injection dies with cavities fashioned in accordance with blueprints of the part to be cast.

Intricacy and accuracy both start with the making of these molds or dies. The patterns cannot be any more accurate than the molds or dies, and the castings cannot be more accurate than the patterns. The master pattern must have all of the allowances for shrinkage, all of the compensations for distortion, built into it. It is not an exact replica of the part to be cast, but is a carefully engineered production tool. The die cavities must have these same features.

Molds or dies must be in sections so they can be opened to permit removal of the finished patterns. Often they have multiple cavities so that a single injection of pattern material will make many duplicate patterns.



(*Courtesy Sperry Gyroscope Co., Inc., Great Neck, N. Y.*)

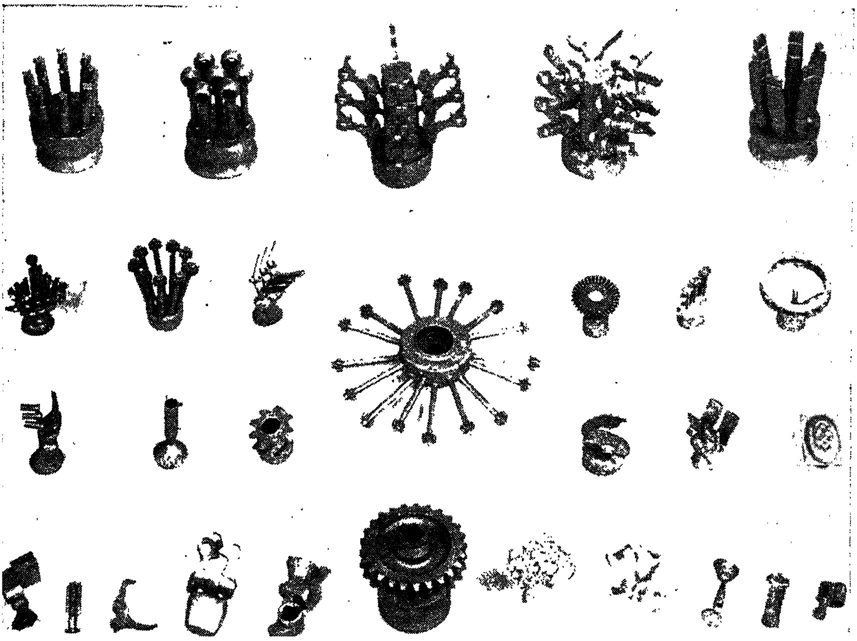
FIGURE 3. A mold, and the dispensable wax pattern it makes.

Depending upon the intricacy and the accuracy of the item to be cast, and somewhat upon sizes of production runs, the making of molds and dies can be anything from an unskilled labor operation to a highly skilled toolmaking job. The tendency in the industry is to use higher and higher grades of tool design engineering and toolmaking skill.

Injecting or casting of the pattern material may be done at pressures ranging from simple gravity to thousands of pounds. The equipment for it may be anything from a tablespoon to a highly complex and thoroughly controlled machine. Again, much depends upon the intricacy and accuracy desired in the finished metal castings. In more than one instance as much as $10,000 has been spent, with profit, upon making the tools for making the patterns for a single intricate cast item.

Step 3. Clustering the Patterns. Dispensable patterns are cast with gate extensions or with special areas to which gates may be attached. The gates, in turn, will be attached to runner members, and these to one or more main sprues, or directly to the down-gate riser or "button." The gates at the castings themselves generally are called the "gating" and the sprues and runners the "sprueing."

All of the sprueing and sometimes the gating is made of dispensable pattern material but seldom of the same material as the patterns themselves. Lower cost materials often can be used for sprues. The point is important because the sprueing and gating may make up more than two-thirds of the weight and volume of pattern material used.



(Courtesy Kerr Mfg. Co., Detroit, Mich.)

FIGURE 4. Typical patterns and clusters.

The group of attached patterns and gates, runners, sprues and sometimes risers is known as the "cluster." Clustering may be a simple hand tool operation. When this is so it is a costly one—costly in terms of wages paid, supervision time, patterns accidentally damaged, and castings spoiled by inaccurate sprueing.

It also may be a mechanical or jig operation involving the use of mechanical motions, heating devices, temperature controls, pneumatic or hydraulic mechanisms. The mechanization of the sprueing operation is one of the most important matters of present day research.

The planning of the gating never is unimportant, almost never can be haphazard. The gating and sprueing with the subsequent clustering governs the ability of the cast metal to fill out the investment cavities, can affect the soundness of the casting, impart directional strength to the casting, raise or lower the time needed to evacuate the patterns, seriously increase or decrease the amounts of metal which must be wasted to scrap, establish the number of castings which can be made within a single invested flask, and have drastic effects upon the costs to perform secondary operations on finished castings.

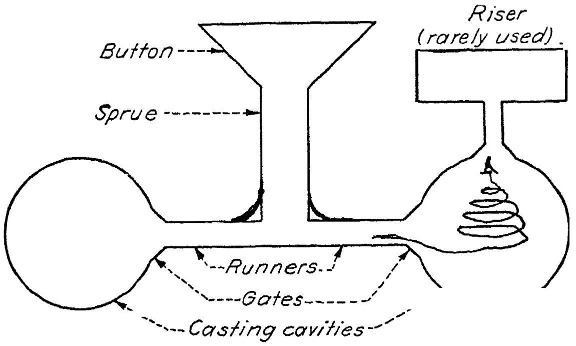


FIGURE 5. Schematic drawing of cluster showing the most commonly used nomenclature.

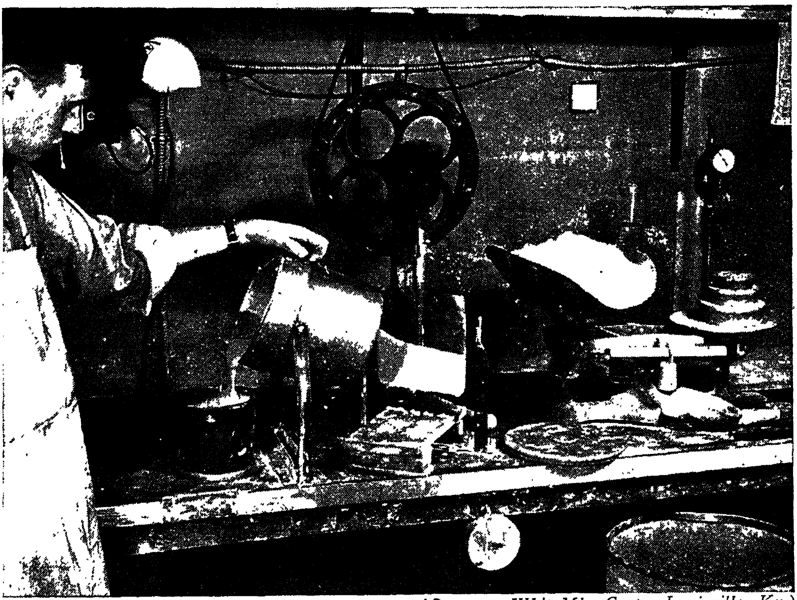
Step 4. Pouring the Investment. The investment material almost always is a refractory plus a binder. But there is no limit to the number of formulas which may be developed for this purpose. Several satisfactory materials may be purchased on the open market, and many precision casters have their own formulas which usually are modifications of standard brands. Nevertheless, experimentation with new formulas is continuous.

Investment materials can be had to meet wide requirements of intricacy of cavity contours, holding of exact dimensions, withstanding of forces of casting, fitting to metallurgical needs, providing of desired surface finishes, removability at reasonable cost, and low overall cost to use. But obviously, no one material meets all of these requirements to an ideal degree for use with all alloys to be cast under all conditions. Many variants of investment formulas must be used.

The investment material must be made liquid and the pattern cluster surrounded by it. The degree of liquidity needed depends mostly upon the complexity of the contours of the cluster. Small holes in the dispensable patterns which the investment must enter and fill, sharp contours such as threaded sections, need sufficient liquidity so the material will enter and fill them completely. But the degree of liquidity also can affect the extent to which the material will completely cover or "wet out" the pattern surfaces. Therefore it affects both the accuracy and the surface finish of the completed casting.

Porosity of the investment must be controlled. Too high porosity can produce bad surface finish; too low can mean that the air does not escape through the pores of the investment as the hot metal is cast and that defective castings accordingly are produced.

The various formulas which meet all of these requirements can range from intricate to simple. An intricate formula may need to be mixed with laboratory accuracy, poured and applied at exactly controlled temperature, vibrated and vacuum-treated just as carefully to remove air bubbles and refine the porosity, allowed to set as ordinary concrete sets but for a time period which is measured with a stop watch, applied in several successive layers, mixed only in quantities to be used immediately, lest it set before it can be ap-



(Courtesy Whip-Mix Corp., Louisville, Ky.)

FIGURE 6. Even the simplest of investment materials needs close control.

plied, and so on. A simple formula can be mixed and applied quite casually, with no serious attempt at exact control. The simple formula usually is lower in first cost of ingredients.

Obviously, no wise management uses any more intricate formula than is necessary. The continuous experimentation with formulas is to obtain the benefits of intricate ones with simple ones, and to find formulas, no matter how intricate, which will solve problems which present formulas cannot solve.

Before pouring the investment the cluster is placed in a steel flask. This flask serves two purposes. First, it is a chamber within which the pattern cluster may be positioned so that the investment material will surround it to the desired thickness of investment wall. Secondly, it is a source of physical or structural strength which makes the investment better able to withstand the forces of casting. The flask may stay in place until the casting process is finished. Usually it is made of scale-resistant stainless steel since it must endure high temperatures.

Most of these flasks are cylindrical. But many casters are using rectangular- or other-shaped ones because they can handle their problems of clustering, sprueing and heat-treating better if the pattern cluster does not have to be fitted within a cylindrical wall.

Step 5. Hardening or Setting the Investment. The process of hardening or setting the investment so that it solidifies, also can be intricate or simple.

This hardening or "setting up" may be a simple matter of placing the flasks on a table and letting them stand there for any time period ranging from a minimum of twenty minutes or so to any longer time convenient for the flow of production. Or the hardening may have to be at controlled temperature, for a closely controlled time period, and even within a controlled atmosphere chamber so that the emission of moisture from the surface of the investment is at a carefully predetermined rate.

Much depends upon the dimensions and contours of the dispensable pattern cluster. Heavy sections (in precision investment casting any section over three-eighths of an inch thick is to be considered heavy) require correspondingly strong sections of investment to withstand the forces of casting. Intricate contours, especially intricate interior contours, may require long and thin cores of investment material, or heavy cores of investment having only very thin supporting areas. The investment material in "setting up" will go through phases of expansion and of contraction. These phases may occur at different times in different sections or areas of the investment, being most likely to occur first in the thinnest sections and in the areas most exposed to the air. If the opposing forces of expansion and contraction in different parts of the investment are sufficient to set up serious strains within the hardened investment, they can cause spalling, losses of accuracy, actual ruptures and other troubles leading to the production of faulty castings. The heat from molten metal compounds these strains while casting.

The two remedies most frequently used for these troubles are (1) to control the setting up process time, temperature, etc., so that the strains are kept within safe limits, and (2) to use investments which are more intricate to apply but which overcome these setting up troubles. An investment which is intricate to apply may or may not also be intricate in the setting up.

Removal of part of the dispensable pattern material may be part of the setting up process. If heat is applied to control the setting up, or if the application of heat is permissible, that heat may cause as much as 97 per cent of the pattern material to become plastic or liquid and flow out. This material nearly always can be used for sprues and gates (described in Step 3) and in some shops is completely reprocessed for use in the patterns as well.

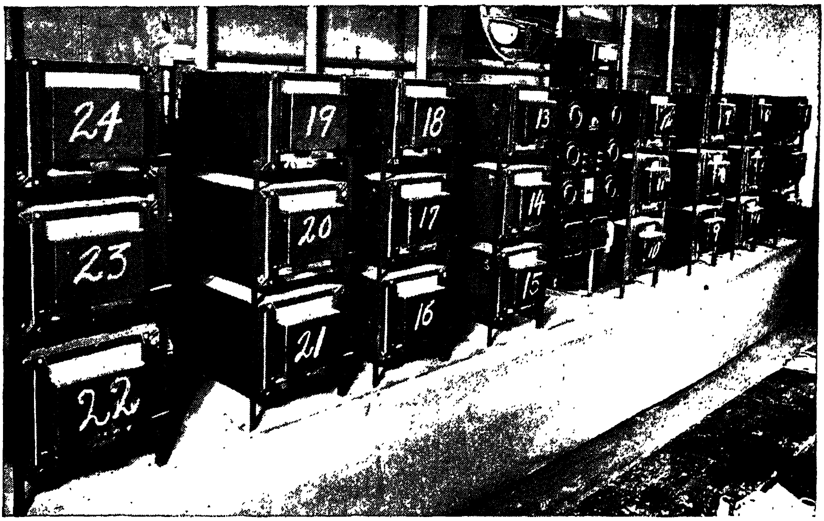
Step 6. Evacuating the Pattern Cluster. The pattern cluster must be completely evacuated in order to leave the cavities into which the metal is to be cast.

Evacuation always is in two steps: (1) the "melt out" in which the main body of the pattern material is caused to flow out of the investment, and (2) the "burn out" in which the last vestiges of pattern material are turned to gas and thus are nearly all removed. There may be a third step, usually called the "dissolve out," in which chemicals are used to remove any oxides (ashes) left by the "burn out."

Evacuation was a rather simple heating process in the days when industrial precision investment casting was only one step away from dental laboratory practices. But now the procedure may involve closely controlled temperatures, the use of boiling water, of low pressure steam, and of vacuum applied to the sprue button. Some of the most exacting specifications of dispensable pattern materials and of cluster designs are laid down because the evacuation problems require them.

The "burn out" once was exactly that; the pattern materials were oxidized at high temperatures. But in the present days of close temperature control it is known that if the pattern material catches fire the temperature goes out of all control. The burn out, therefore, is more likely to be a "vaporize out," with every precaution taken to prevent any combustion.

The "dissolve out" is needed when low fusing-point metals are used as patterns, or any other materials which will not vaporize out completely. It is a complication of the evacuation step because it demands a pause in that step, a cooling down of the investment between the last part of the setting or hardening and the final heating for casting. Without this, or any other pause, the flask with its investment and pattern materials usually is slowly heated for the melt out, more rapidly heated to the burn-out point, then rapidly heated to the casting temperature which commonly is well above 1,000 degrees F.



(*Courtesy Whip-Mix Corp., Louisville, Ky.*)

FIGURE 7. Evacuation chambers need close control. *Note the electrical control instrument panel in the middle of the bank.*

The melt-out step is likely to be somewhat slow and at the lowest practical temperature, for several reasons. There is the matter of recovering as much of the pattern material as possible, if any can be reused. This must be done at the lowest practical temperature so as to change the chemical nature of the pattern material as little as possible. The melt-out step may be coincident with the heat-controlled final hardening of the investment, as described under Step 5.

When patterns of heavy sections are used, or the contours include very thin sections of investment materials, the behaviors of the pattern materials and the investment materials under rising temperatures may be highly important.

Investment materials can go through several critical ranges in which their rates of thermal expansion change, and dispensable pattern materials can have even more of these critical ranges. Coefficients of thermal expansion of investment and pattern materials seldom are the same. Until the softening or mushy temperature of the wax is reached, therefore, the investment and the pattern cluster always are opposing each other in their rates of thermal expansion, and sometimes one is expanding or otherwise changing contours and dimensions while the other wants to contract or otherwise move in the opposite direction. Such conflicts can result in spalled walls of the investment, broken sections, rejected castings.

The pattern material commonly is a good heat conductor, the investment material an outright heat insulator. Consequently the pattern material tends to heat up first, to expand first, and to expand in the direction of least resistance which usually is toward the main sprues and along them toward the button or riser. If the sections are heavy enough this movement also can result in spalled walls and fractured sections.

The investment material itself must be heated up slowly enough so it does not fight itself by having thin sections become materially hotter than thick ones and so have different portions simultaneously undergoing different extents of thermal expansion. Investment materials commonly have very little ductility and will crack if not heated evenly.

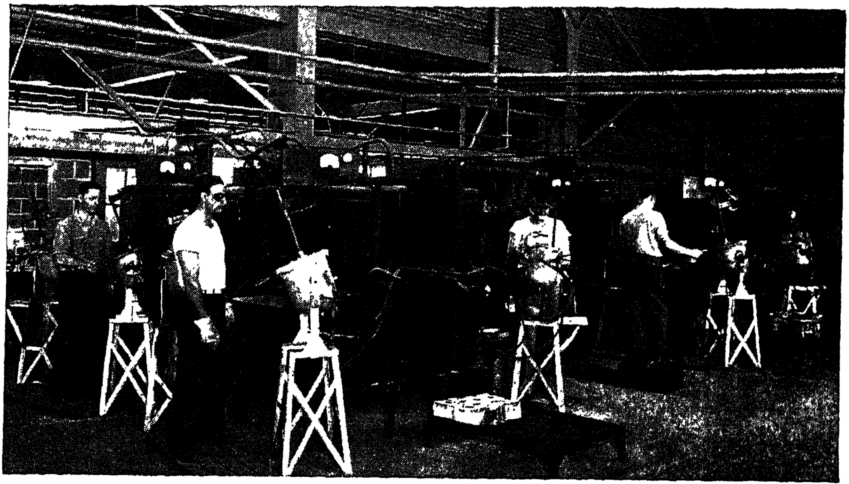
The evacuation process looks like a simple matter of melting and burning out the pattern material. Actually, it can be the most intricate and difficult step in the production sequence.

Step 7. Bringing the Flask to Casting Temperature. The correct casting temperature can range from "chilled" or less than room temperature, to over 2,000 degrees F, depending upon the alloy to be cast, the dimensions and contours of the castings, and the metallurgical conditions desired in the metals. This process must be controlled so that no dirt or foreign matter enters the flasks. Otherwise it involves no temperature control principles not described under Step 6.

The completed investment within its steel flask, with the pattern material completely evacuated, and at the desired casting temperature, is known as an *invested flask.* The great bulk of the costs of this precision investment casting process commonly is in the steps which result in an invested flask.

Step 8. Casting the Metal. The selection of metals to be cast can require considerable judgment.

First cost of these metals is relatively less important than to most precision production processes. The metals are the only raw materials. In most precision processes the costs of materials and labor are likely to be nearly equal to each other. In precision investment casting the cost of labor alone can range from four to as much as eighty times the cost of raw material. Add to this labor cost those of supervision, of such materials of production as investment and pattern ingredients, of tooling, of equipment and of overhead, and it will be seen that the amount to be gained by casting less expensive alloys is relatively little.



(Courtesy Haynes Stellite Co., Kokomo, Ind.)

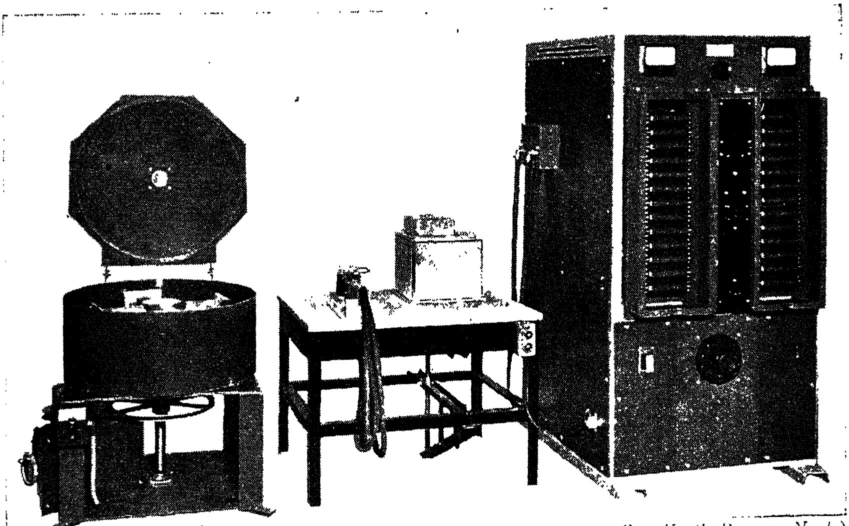
FIGURE 8. Arc furnace low-pressure casting machines ready for action.

Some of the more expensive alloys can be cast much more easily than cheaper ones. Some stainless steels, for example, are far less intricate to cast by this process than are gray irons.

The precision investment casting method can achieve such high accuracies and complex contours that it is a favored method for making parts out of metals too high in cost to permit machining into scrap or too hard or otherwise difficult to fabricate by machining.

Melting of such alloys usually must be done in carefully controlled furnaces or crucibles. Fluxes or other oxide and slag preventives and controllants may be needed.

The pouring or casting of the metals almost always is done by centrifugal force or under pressure. This force and velocity must be controlled in accordance with the alloy and with the contours and dimensions of the investment cavities.



(Courtesy Ecco High Frequency Co., North Bergen, N. J.)

FIGURE 9. (*Left to right*) Centrifugal casting machine, high frequency melting equipment, high frequency spark gap converter.

With close control of the casting process and careful planning of the sprueing and gating, it is possible to vary the directional strengths of castings made of some alloys. This adds just that much more to the ability of the process to produce castings having exactly the qualities desired by the product engineers. But it also adds to the overall intricacy of the process itself.

Other qualities can be controlled. Castings can be made highly porous, extremely dense, or with widely desired degrees of solidity. Tensile and other strength can be greatly increased over those obtained by some other processes. Metal ingredients of an alloy can be caused to redistribute themselves in various sections of castings so that some sections are harder than others, or are of higher specific gravities, have more corrosion resistances, have higher lubricities, and so on.

A great deal of special alloying is done. Since the ingredients of the various alloys are mixed and melted in very small batches, many metallurgists believe that it is easy to control their proportioning, although the cost per pound for exact proportioning is higher than proportions controlled by the general averages methods used in large steel mills which melt by the ton rather than by the pound. But this higher cost is to be judged by the fact that metals costs make little difference to the overall costs of precision investment casting. This factor will lead to the development of many new alloys.

Special alloying may have several purposes, among which are: to obtain alloys which are easier to process by this method, to obtain higher strength characteristics or higher hardness or higher corrosion resistance or other desired qualities in the finished product, to consume scrap or other quickly available metals, to compensate for losses of some alloy ingredients in the melting and casting and thus control the proportioning of the final product.

Precision investment casting has permitted the metallurgist to solve many problems which previously could not be solved within practical commercial limits. It has many such problems which remain to be solved, and can require high intricacy of metallurgical control.

Step 9. Removing the Investment. When the castings have cooled and solidified there remains a hardened investment within a steel flask and inside of the investment the castings with their sprues. The flask and investment must be removed, and this involves destroying the investment.

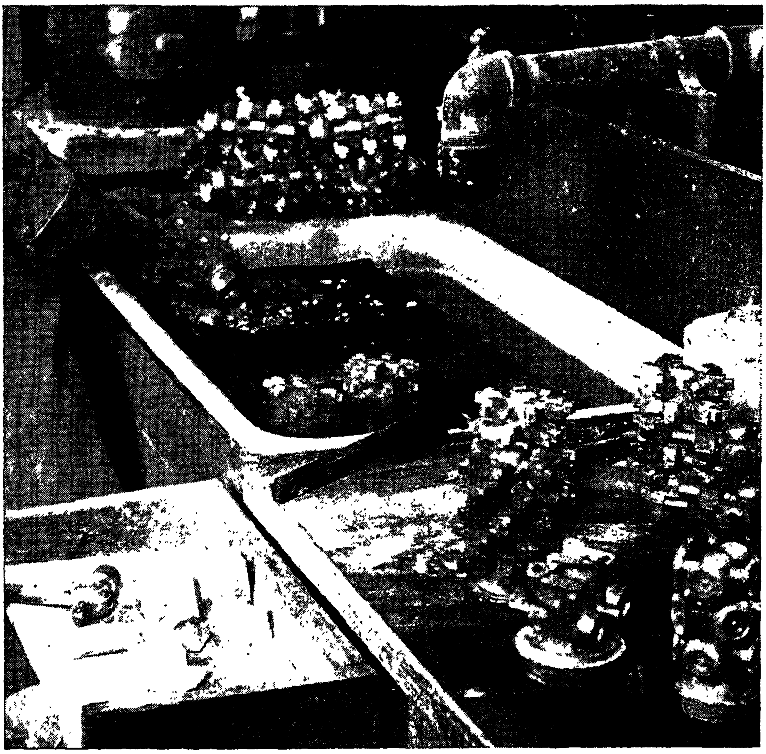
Some investments are soluble in water and may be removed by immersing in water followed by suitable rinsing and drying of the castings and sprues. Others are soluble in weak solutions of caustic soda or other chemicals, but these usually require immersions of twenty-four hours or longer.

The investments commonly used for ferrous castings must be cracked and broken away by the use of hammers, pneumatic tools, shot or abrasive blasting and similar forceful methods.

Two or more investment materials may be used for the same invested flask. A common practice is to use inserts of a material which is soluble in caustic for long holes and for other intricate orifices and interiors in castings, and use more ordinary investment materials for exteriors and other parts. In these cases the exterior investments may need to be broken off, after which the interior investments are dissolved away.

Removal of the last particles of investment may be done by shot or abrasive blasting, by tumbling, or in abrasive blasting machines which tumble as they blast. This same operation may serve to improve surface appearances.

Investments at thin or delicate sections of castings, and within cavities which have orifices smaller than their main diameters, can be the most difficult to remove. Care must be taken not to damage the thin or delicate sections. Sometimes the investment material must have a small hole drilled into it as a starting point for the abrasive blasting material to attack.

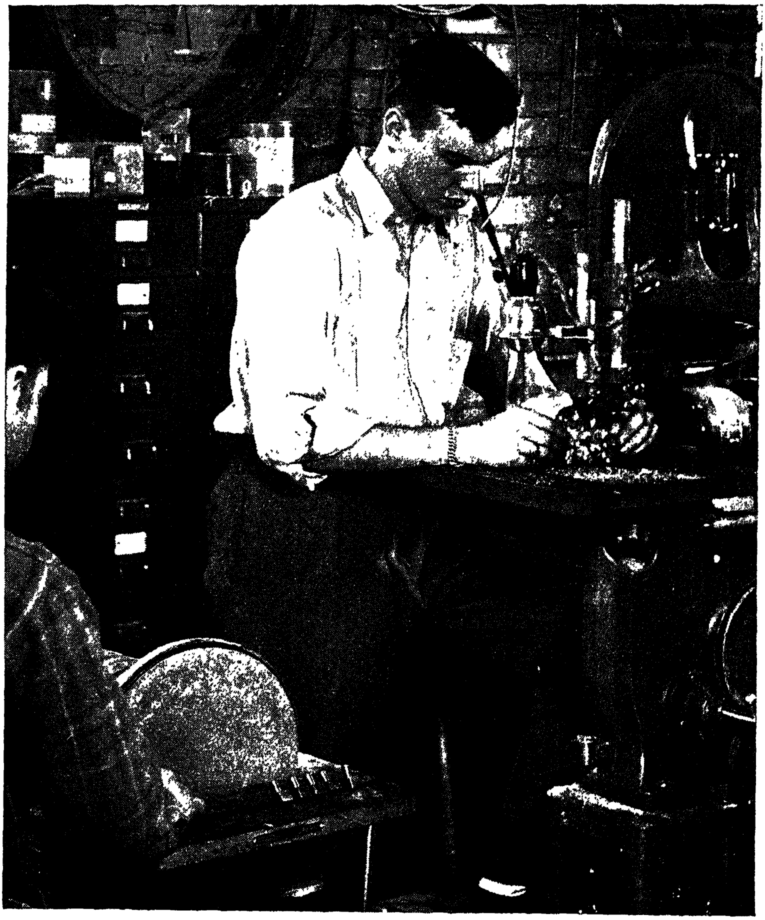


(Courtesy Whip-Mix Corp., Louisville, Ky.)

FIGURE 10. Investments must be broken or dissolved away.

Step 10. Cutting Away the Sprues and Gates. Depending upon the shape of the cluster and the machinability of the cast metal, the gates, runners and sprues may be cut away from the castings by using a band saw or a high-speed, abrasive cutting disc. The band saw cannot be used, of course, unless the cluster is so shaped that the saw blade has straight line clearance while being in position to cut at the desired place. And many of the alloys cast are too hard for sawing.

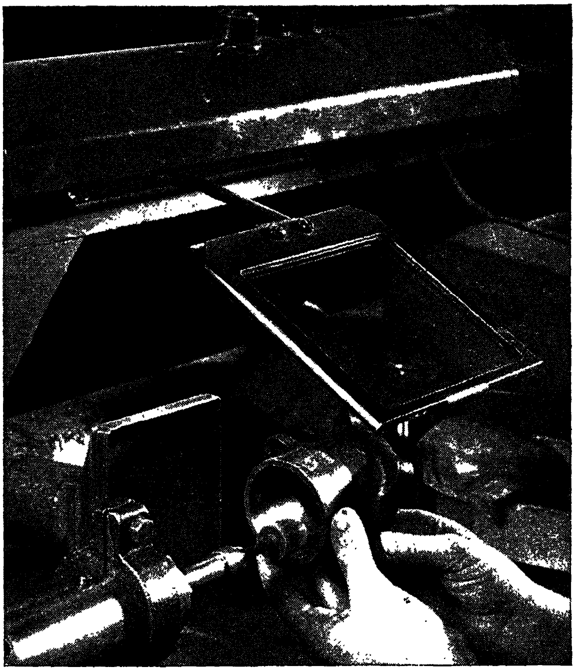
Gates may be cut off right at the surface of the casting thus making a finishing operation of the cutting. Or they may be cut close to that surface but leave a slight extension which must be ground away.



(*Courtesy Whip-Mix Corp., Louisville, Ky.*)

FIGURE 11. Some clusters can be band sawed; others require the friction disc.

This final grinding of the gate sometimes is made a finishing operation to increase the accuracy or modify the contour of the casting. Thus, if castings of a given size would normally come to plus or minus 0.003 inch on their longest dimension and it is desired to hold that dimension to plus or minus 0.001 inch, the part may be gated at one end of this dimension, the dispensable patterns so made that the castings will come at least 0.002 inch oversize on that dimension (plus 0.002 to plus 0.008 inch limits) and the gate grinding operation be used to bring the dimension down to the desired plus or minus 0.001 inch. Similarly, this grinding operation may be done with a specially contoured wheel to generate on the casting a contour which would be difficult to cast to the desired accuracy or smoothness.



(Courtesy Haynes Stellite Co., Kokomo, Ind.)

FIGURE 12. Final operations may include any of those common to precision machine shops.

The gate extension left by the band saw or abrasive disc sometimes is designed to be a work holding area by which the casting may be chucked or otherwise held while machining, plating or other finishing operations are performed.

Removal of the gates and sprues is a machine-shop operation. By the time the casting process reaches this stage it has produced a semifinished metal material ready for final operations. But the methods planned (Step 1) for these operations may greatly influence the clustering (Step 3).

Step 11. Final Finishing Operations. The finished castings may be machined, ground, pickled, plated, subjected to any of the machine-shop operations.

Balance between the intricacies to be achieved by casting and by these final methods must be careful. By machining some contours instead of casting them, it sometimes is possible to get more than twice as many castings into a single clustering, with consequent reduction of the cost per casting by more than one third. By casting one small hole instead of the desired ten holes, casting that one very accurately as to location, then using it for tne location or control or guide hole for a ten hole gang drill, it is practical to reduce greatly the costs per finished part. Dozens of similar examples could be cited.

Precision investment casting is one of the most versatile arts ever offered to the product designer and the production man. But enthusiasm for its techniques should not cause it to receive assignments which can better be performed by other processes.

Overall View of Precision Investment Casting

Modern precision investment casting is a distinctly new resource of the production line. It has many roots and antecedants in ancient industrial arts; nevertheless its present-day form is an abrupt departure from traditional methods.

It is capable of solving thousands of problems for the product designer and the production manager. Its capabilities also can be grossly misunderstood with the result that problems are assigned to it which might much better be solved by other production methods.

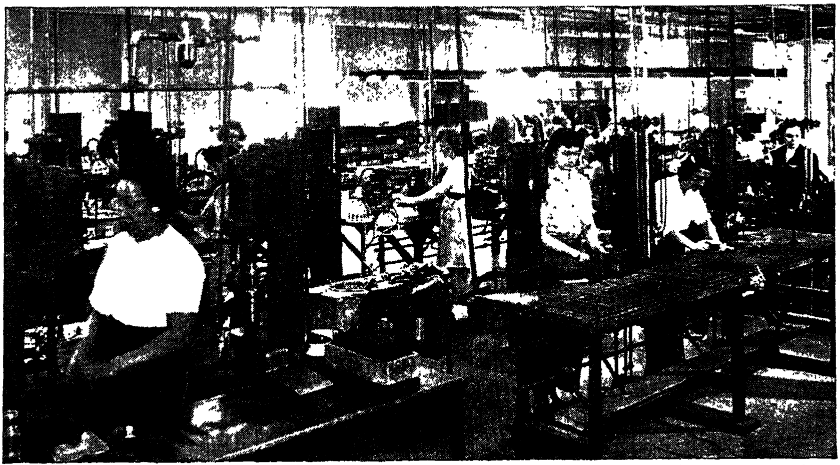
(1) **Not a "Cheap" Process.** To quote dollar figures on the costs of precision investment castings would be futile since the markets for materials and labor could change drastically before this book is read. But let the production-trained engineer calculate that at least eleven production steps are needed, and that nine of these must be under the closest of precision control, and that investment materials as well as pattern materials are expended, and that anywhere from 15 to 90 per cent of the total metal cast into a flask consists of sprueing and other waste. It should be clear from this that "per piece" costs of precision investment castings are as high as those of any ordinary production processes involving equally high precision.

The weights of finished castings run from a small fraction of an ounce to more than seven pounds, with still heavier and larger ones occasionally produced by this process. Thus a single pound of finished castings may contain over 100 pieces or may be less than one piece.

In general, the smaller the size of the finished casting the greater is the percentage of waste metal for sprues and gates. But this relationship between weight and waste is by no means a straight-line one. Smaller castings do, in most instances, cost more per pound of the same alloy to produce than larger ones. And on a per-pound basis all costs are much higher than those for some of the other methods of casting.

Precision investment casting should be used only for the production of parts which are costlier, or even are impossible, to make by other methods. Judged upon this basis the process is receiving assignments to make thousands of different products.

(2) **Not a Process for the "Tyro."** Precision investment casting sometimes has been represented as a process which almost anyone can operate with very little knowledge and with small amounts of invested capital.



(Courtesy Haynes Stellite Co., Kokomo, Ind.)

FIGURE 13. Pattern molding is not a cheap process, nor one for the tyro.

In rare cases this picture may be correct. But this process requires at least eleven separate steps, each of which needs equipment, tooling, knowledge and skill. The successful operator usually needs some knowledge of metallurgy, of machine-shop practices, of general factory management, of toolmaking and of product design.

To all of this he must add special knowledge of the process itself. The most successful operators try to broaden their management staffs to include men skilled in ceramics chemistry, wax chemistry, and the specialized tool design which has its parallels only in die casting, metals extruding, and plastics molding. Since this process often is used for making machine parts which must bear the highest stresses with the least weight and sizes, engineers highly skilled in the techniques of inspecting and testing materials may be needed.

When the metals to be cast are very hard or otherwise are highly special, particular knowledge of their metallurgy may be necessary. And for secondary operations on such castings the management may need knowledge of special machining, grinding and other techniques.

Invested capital requirements can vary as widely in this as in any other production process. But there is no sign that the ratio of fixed plus operating capital to gross sales volume can be any lower in precision investment casting than in the general run of machine shops, stamping plants, die castings or other factories which make precision products out of metals.

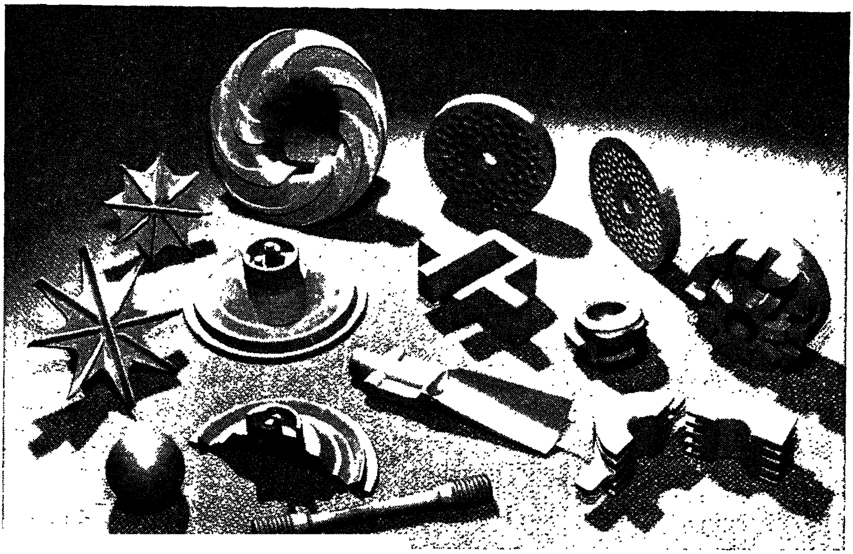
(3) **A Process for Making Complete or Nearly Complete Products or Parts.** The conception that casting is a process for the first of the primary operations only, and that a casting is only a raw material for the production line, should be discarded very nearly as thoroughly for precision investment casting as it has been for die casting.

Precision investment castings receive secondary or completing operations more often than die castings. They lend themselves more readily to becoming the starting points for other production line techniques. But the great majority of parts and products made by precision investment casting are complete when their gates have been ground off or when a few very minor secondary operations have been performed upon them.

(4) **A Preferred Process for Intricate Contours.** Of all production processes this one seems to have the fewest limitations upon the intricacies of contours both exterior and interior, or upon the combinations of intricate exterior and interior contours, which it can produce within commercially practical costs.

Curves of successively differing radii, "cam shapes," gear teeth, threads, fine surface design detail, thin edges, severe undercuts, holes of almost any desired shapes, chambers having entrances smaller than their main diameters or interior dimensions, holes which follow other than straight line paths, almost any contour which is intricate for other processes is relatively simple for this one.

Of course, high intricacy of contours is not achieved at the same overall cost as low intricacy. The making of the master model or of the pattern mold or die is higher in cost, sometimes drastically higher, for high intricacy. Costs of this process in these cases may be low only as compared to those of other processes for making the same product.



(Courtesy The International Nickel Co., Inc., New York, N. Y.)

FIGURE 14. Most precision investment castings are of high quality alloys, high precision, and intricate contours.

Aside from the master model or mold cost there is no straight relationship between complexity of contours and cost of the process. An irregular contour may be less costly than a regular one for precision investment casting. For example, a long thin piece of curved and tapered contour could be less costly to cast than a perfect cylindrical shape of the same size and weight. In this example as in dozens of others, what is simple for any common machining process may be intricate for precision investment casting, and the reverse. What is well designed for one of these production methods may be poorly designed for the other.

(5) **A Process for Accurate Dimensions.** When any process includes the machining of metals or the forming of metals with tools which have been machined, intricacy of contours must be judged

in relation to complexity and to dimensional accuracy. It always is easier to achieve complexity without close accuracy, or accuracy without complexity, by such methods.

The dimensional accuracy of precision investment casting, by contrast, has very little relation to complexity of contours. If this process can achieve an accuracy on a given dimension, for example on the length of a piece, it makes little difference whether the contours within that length are curved, irregular, angular, re-entrant, or involved.

The overall accuracy of precision investment casting is equivalent to that of good machining, and in some cases, to that of grinding. Thus the normal accuracy of the process is on the order of plus or minus 0.003 inch per dimensional inch with plus or minus 0.001 inch the tolerance limit of fineness. This tolerance limit can be held only on dimensions of 0.25 inch or less. But when required to do so the process generally can cut these tolerances in half and work to plus or minus 0.0015 inch per inch with plus or minus 0.0005 inch the limit of tolerance fineness on very small dimensions. Still closer tolerances have been held but they are to be regarded as "special production" and not standard practice.

The process offers the product designer and the production man certain facilities far beyond those offered by the common machining production methods with which they are familiar. These facilities involve the selection of control areas for further machining, assembling or fastening, the selection of location areas, shoulders, holes, etc., for guiding tools in secondary operation machining or grinding, and the selection of reference areas for inspection measuring. This fact makes it unusually easy to achieve close accuracies by secondary machining and grinding operations on these castings, and to assemble parts into highly accurate units.

Precision investment casting eliminates many of the accuracy problems common to other production methods, but also has accuracy problems peculiar to itself. For this reason an entire chapter of this book is devoted to accuracies and their effects upon product design.

(6) **A Process for Controlled Surface Textures.** Precision investment casting never produces surfaces of superfinish quality. Its surface smoothness is measurable in terms of thousands of an inch but not in millionths.

The surfaces possible to achieve differ with alloys and with casting methods. They are smooth and clean and generally of the qualities produced by ordinary machining, far smoother than ordinarily obtainable by sand casting. But they are cast surfaces. They have the familiar matte finish of cast surfaces. Only in rare instances, when special techniques are used, can the surfaces be cast "bright" or polished, and this can be done only with a few alloys.

Within this matte limitation surfaces can be made porous or non-porous or with various degrees of roughness or other appearances at will. But when any other appearance than the normal "as cast" one for any alloy is wanted it usually can be obtained more cheaply by a secondary operation than by varying the precision investment casting process.

(7) **A Process for Alloys Too Costly to Waste or Difficult to Fabricate by Other Processes.** The development of the precision investment casting process is following three separate paths:

(1) Its use for the common bronzes and steels, the lower ranges of stainless and other lower alloy steels, the aluminums and magnesiums, etc., in which it must stand or fall by its abilities to solve problems of contour complexities with dimensional accuracies.

(2) Its use for the precious and other high-cost metals where contour complexity generally is more important than accuracy, but the avoidance of wastage of metal to scrap is highly important.

(3) Its use for tungsten, cobalt, high alloy steels and other metals which are difficult to machine or to grind. Included in this group would be some alloys which are easy to machine but difficult to solder or weld into complex assemblies.

There are literally hundreds of alloys which are ignored by the product designer, or else are used only when mandatory, because they are too hard to machine, or they tear while being machined, or the scrap losses from machining, stamping or forging them make the metals costs for the finished parts prohibitive.

Not all of these alloys can be fabricated by precision investment casting. The product designer must make as intelligent a selection of the alloys to be precision investment cast as he would of those to be machined. But this process is making available to industry dozens of different alloys which formerly were pushed aside as being too costly to fabricate, and in so doing is decreasing the weights and dimensions of products, eliminating heat treatments and other costly operations, eliminating welding and other assembly operations, permitting product designs which formerly were impossible.

Some of the most important high temperature parts for airplanes, such as some designs of turbine blades, are said to be impossible to manufacture by any other process than this one. And there is no important field of machinery or of other metal products which is not being seriously changed by the ability of precision investment casting to fabricate the "costly" and the "difficult" metals.

When this process is being used to fabricate costly or difficult alloys, the balances of production cost factors which determine what contours and accuracies to cast and what to machine or to achieve by other secondary processes change radically. In general, the higher the cost or difficulty of machining the alloy, the more the contours and dimensions which should be obtained by casting, and the higher the cost per piece or per pound of metal of the casting process.

(8) **A Process Requiring Little Floor Space and Low Production Time.** More than one successful precision investment casting shop is being operated within 1,500 square feet of floor space. The process employs very few bulky machines and almost no heavy ones other than the toolmaking equipment which is used for making master patterns and injection dies. Very rarely is extensive materials-handling equipment needed.

Finished products ordinarily emerge from the casting production line within 24 hours of the time when the first production step is taken, and overall production times of less than four hours can be had with some alloys and investments. The precision investment casting process often has taken over the production of products which by previous methods required eight whole working days from the first to the last steps in their production sequences.

(9) **Extremely Flexible in Setup.** Once the master patterns and other tools are made, a product usually can be set up for production in a few minutes. This compares to the hours and even days of setup time needed for automatic screw machines, high intricacy stamping dies, and most other equipment for producing complex contours.

If desired for flexibility of production, many different products can be sent down the production line at the same time. The different flasks can be routed to different casting machines for different weights of castings or even for different alloys, casting temperatures, physical characteristics of finished metals. Or when one alloy is to be cast into several parts of varying sizes and shapes, the different parts sometimes can be clustered together for investing and casting in the same flask.

There are, of course, limits to this flexibility. Some alloys and parts need entirely different investment materials than others and entirely different treatments. But precision investment casting is by far the most flexible process for producing intricate precision metal products.

(10) **An Excellent Process for Product Development.** The production of millions of duplicate parts may be most economical by precision investment casting; the average production runs assigned to this process probably are as large as the average for any other. But precision investment casting also lends itself to the making of extremely small quantities, especially when common sense is used in selecting the contours to be achieved by casting and by machining or by other secondary operations. Therefore a large number of variants or modifications of an experimental part or product can be made by this process and by trial and error the best one for the task in question be selected.

Precision investment casting has been known to cut months from the time normally needed for the development of a new product or the improvement of an old one.

(11) **A Process for Toolmaking and Development.** Tools, dies and their parts can be made by this process at low costs and of metals or into shapes which the toolmaker never would attempt to machine.

(12) **A Resource for Subcontracting.** A large number of well organized contract shops are operating in the precision investment casting field. The sales engineering personnel of many of them are well trained and highly capable. Many of these shops specialize in limited ranges of alloys, others cast all castable metals. A good contract shop can be found for any product which "belongs" to this process.

Patent Situation

As might be expected in an industry of this type, several patents have been granted and they are in various stages of litigation as to claims, counter claims and validities. Some 300 patents are estimated by authorities to apply to different phases of the process. Among the patent holders are Austenal Laboratories, Inc., Carbon and Carbide Chemicals Corporation, Thoger G. Jungersen, Kerr Mfg. Co., and Whip-Mix Company. This book expresses no opinion as to the validity or ultimate outcome of any patent litigation which may be in process.

Chapter 2

Products Cast in Large Quantities

Production runs of over 100,000 duplicate parts are not uncommon to precision investment casting, and runs of over 1,000,000 are by no means unknown. Nevertheless any run of over 5,000 may be regarded as large, any from 1,000 to 5,000 as medium, and any of less than 1,000 as small.

There is no logical reason for the selection of those figures. These classifications of "large, medium and small" are defined on the basis of the outright pragmatism that that is how the general run of jobbing precision investment casting shops find them to be. The figures therefore are convenient for general use. But in the instance of a specific cast product 10,000 could be an unprofitably small run or 1,000 an amazingly large run.

Large production runs by any process whatever are made for two general reasons:

(1) The sales volume of the item is large.

(2) Even though the sales volume is low the production difficulties or other problems can be solved only by the methods and the economies of large volume production.

The two situations tend to be alike in that the higher the volume the higher can be the justifiable cost of the planning and the tooling. Also, the higher the precision or duplicate production runs of an item the more anxious is every known production method to take over its making. Therefore, on high production runs precision investment casting must beat every other method at its best.

The reasons why precision investment casting wins these tasks are, in general order of their frequency:

(1) Lower overall costs.

(2) Original product, or else an improved design, cannot be made economically by any other method.

(3) Use metals which are hard to machine, to stamp, to forge, or to fabricate by any of the common processes.

(4) Combine two or more parts into one, eliminate soldering, brazing, welding, other joining operations.

(5) Secure special contours which provide equal strength with greatly reduced weight. This is especially useful in aircraft, business machines, others in which weight is unwanted.

(6) Obtain special contours which better distribute dynamic stresses and eliminate fatigue failures.

(7) Obtain better dynamic balance, eliminate inertia and vibrational problems.

(8) By better strength for weight distribution eliminate difficult heat-treatments.

(9) Eliminate wastage of metals to scrap, especially of high cost alloys or of metals which are in short supply.

(10) In many instances, greatly reduce the sizes of production runs necessary for economy. But there are instances in which the production runs must be raised if precision investment casting is to be at its highest economy.

(11) Free the time of high accuracy, high production fabricating equipment of various kinds for more profitable use on other products.

(12) Reduce the cost of the precision investment casting process itself. Like any other, this process is subject to improved tooling or higher production tooling economies if the production lots are large enough to justify tool costs and high production equipment usage. And while this factor can vary so much that generalizations are likely to be misleading, the costs of master patterns and of planning and of experimenting can be high enough so that they need to be spread over large production runs. Costs per finished precision investment casting have been reduced as much as 70 per cent when production runs were raised from a former 500-piece lot to a present 100,000-piece lot.

Some Illustrative Examples

Higher Price for Greater Strength. On a fishing pole the entire flexible area from the stiff handle or butt is the "tip" and the extreme end through which the line is threaded is the "tip top."

For salt water fishing with its heavy lines these tip tops had been made of nickel silver stampings, several parts being soldered together. The resulting product was corrosion resistant but was easily bent or deformed in the rough handling incident to fishing. Precision investment cast tip tops made in one piece of S-Monel alloy cost slightly more, were more corrosion resistant, and were so much stronger that as a common sales demonstration a 220-pound man would stand on one without deforming it. Production runs were large because sales were large.

Contours Plus Abuse-Resistance. Sewing machine parts, especially for industrial sewing machines, never have been able to obtain enough intricacies of contours to satisfy all of the ideas of their designers. These parts are variously subject to abrasion by the sewing threads, to the shock loads and hammering of frequent reversals of directions of movement, to rusting when in storage, to corrosion by perspiration from the hands of machine operators and by products sometimes contained in the threads and the fabrics. Sometimes all of this is amplified by the fact that workers and their supervisors do not understand the production machines. Precision investment castings made of specially selected metals solve many of these problems. This process also lets abuse-resistant contours be designed.

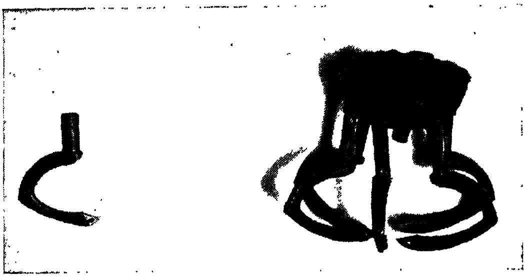


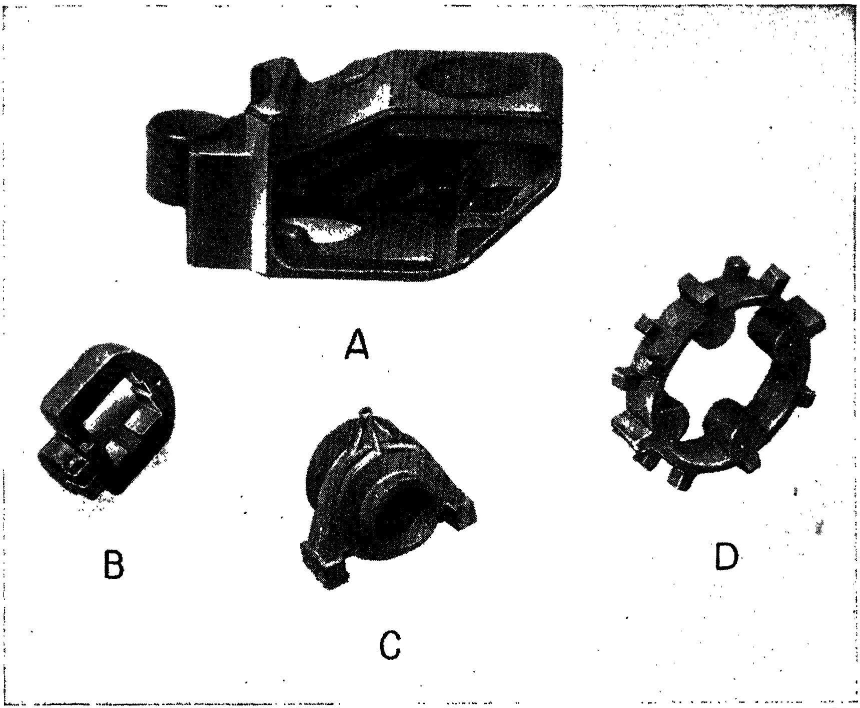
FIGURE 15. Burlap sewing machine needles.
Left: as cast. *Right:* clustered.

Heavy Shock and Vibrational Loads. Air hammer parts may need to be of intricate designs but made of hard-to-fabricate metals which in lightweight and small parts can take heavy and continuous shock and vibrational loads. One end of such a part may need a different heat-treatment than the other end. Precision investment castings can provide more durable metals, more intricate design features, and at the same time be low enough in cost so that their replacement when only slightly worn can be encouraged and can lead to increased efficiency of the tool and to reduced maintenance costs for the other parts with which they work.

Extra Cost for Hard Service. Slide fastener parts intended for the extreme service of all-weather water-resistant tool bags are made of the extremely hard and tough metals which, to these intricate "hook" contours, could be made only by precision investment casting.

Deep and Clear Bosses. Medals made of 87.5 to 12.5 bronze ordinarily would be made on coining presses. In lot of over 2,000,000, precision investment casting proved able to provide deep and clear bosses of intricate design and at somewhat lower cost.

Intricacy at Lower Cost. Precision instrument parts made of beryllium copper had had production costs of $0.66 each. By wise division between casting and secondary operations they cost about $0.25 for the casting plus $0.05 for tapping one hole and for anodizing, a total saving of about $0.36 per part.



(Courtesy Arwood Precision Casting Corp., Brooklyn, N. Y.)

FIGURE 16. A. Beryllium copper instrument part. B. Magnesium guide part. C. Bronze electrical coil housing. D. Magnesium motion control part.

Lug Brazing Eliminated. Dynamic balancing rings made of 303 stainless steel were about 7 inches in diameter, made of 0.040-inch thick stock, had heavy lugs which did the actual counterbalancing when correctly placed to offset dynamic imbalance of high-speed rotating shafts; the rings were made of tube stock, the lugs were brazed on, the thermal contraction from the brazing heat tended to force the rings out of round or to put weakening residual stresses in them. The rings complete with lugs were precision investment cast with resulting higher accuracy and strength. An unexpected factor was that the precision investment cast rings would withstand a substantially greater reverse bend test than would the original ones.

Gang Drilling of Small Holes Avoided. Meat grinder discs made of a high nickel alloy, high in corrosion resistance, and also able to withstand abrasive or frictional wear of mating parts, had to have dozens of small holes through them, the depths of the holes being more than ten times their diameters. Such metal would be difficult to drill at all, especially costly to gang drill with small drills since the spoilage and the machine-down time from broken drills would be high. Several thousand of these parts were precision investment cast at comparatively low cost.

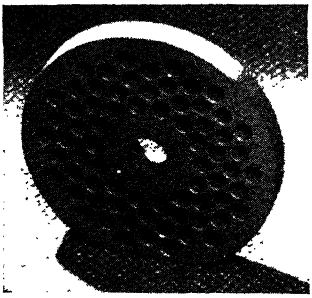


FIGURE 17. Meat grinder disc made by precision investment casting.

Cam Saving on Cost of Actuated Parts. Small parts on a textile machine are actuated by a ring cam which is more than ten inches in diameter, there being some 1,400 of these parts in continuous actuation by the cam. Since the parts are too light in weight to fall back down rapidly enough after being lifted by the cam surfaces, they must bear on one surface which lifts them and on another which pulls them down. The original cam was a solid ring forging which could have the necessary cam curves at its top and bottom edges but required the actuated parts to have one lug to ride on the upper cam surface and a second lug to ride on the lower cam surface, the upper surface to lift the part and the lower to pull it down. The present cam is made of several precision investment castings mated end to end to form a ring. Direct cost saving on the cam itself is more than $8.00. But the present cam is a channel type, the channel following the true cam path and being cast into the inner face of the cam. The actuated parts therefore need only one lug to fit into this channel, the lower side of the channel doing the lifting and the upper side the pulling down. Such parts cost about $30.00 less per thousand or at least $40.00 less per machine. Such a channel could be finished in the inner face of the forging only at an impossibly high machining cost. Net saving on the machine is at least $8.00 on the cam and $40.00 on the actuated parts, or a total of $48.00.

Highly Hardenable Coupling Parts. Pump couplings are made of Nitralloy and then nitrided to have wear surfaces of hardnesses corresponding to about 1,100 Brinnel. Contours would be very difficult to fabricate by machining. Therefore the parts are precision investment cast.

Corrosion-Resistant Pump Rod Ends. The pump rods in this application can be made of any long-wearing and rust-resisting metal but the rod ends come into continuous and moving contact with material which is corrosive and slightly abrasive. The rods are machined of bronze, the rod ends precision investment cast of stainless steel; rod is joined to rod end by brazing. The structure is far less costly than if machined out of solid stock.

$20.00 vs Eight Days' Machining Time. Covers for precision instrument cases are made of S-Monel metal for corrosion resistance and other properties, and must fit intricate contours of the cases with moisture-tight completeness. These formerly took eight days apiece for hand machining time; now they require $20.00 each for a precision investment casting plus a slight amount of secondary operation finishing.

Long-Wearing Bearing Plates. Bearing plates of intricate contours were machined with allowances for hard surfacing deposits, hard-surfaced by freehand arc welding methods, then ground to true contours. Now they are precision investment cast of Stellite. and ground only for a slight amount of final finishing. The performance and the accuracy are superior, the cost reduction is drastic. And the welding department has time free for urgently needed work.

Accurate Turnbuckles. The buckle parts of turnbuckles were wanted in slightly varying lengths and internal threadings, highly accurate, of metal that would be hard, tough and corrosion resistant. There was a limit on permissible cost. By arranging to make these in large enough quantities so that three production runs would keep inventory supplied for a year, precision investment casting tools could be paid for, with molds large enough to inject seven varied sizes at a time, and flasks which would produce forty-two buckles per pouring. On this basis the buckles were produced within the costs limits. Subsequent operations were threading, hardening, and polishing.

Relieve Time of Drop Hammers. At a time when the drop hammers for forging scissors blades in a cutlery plant were overloaded with work and good forging stock was difficult to obtain, precision investment casting was considered as a means for producing the blades out of readily obtainable scrap metal of an alloy superior for this purpose to the alloy generally used. Experimental production runs proved that precision investment casting could produce blades of highly desirable straightness, sharpenability, balance, and the springiness which enables scissors to be "set up" or adjusted in relation to each other for proper cutting. It is not known at this writing whether or not this business was placed. The cutlery industry likes to stick to traditions and the use of drop hammers is one of them. But it was found that with production runs of not less than 50,000 pieces, enough for 25,000 scissors, precision investment casting would be competitive in costs.

Reduction of Welding Costs. Tap setters of 18–8 stainless steel for stainless steel beer barrels were wanted in extremely low carbon for weldability. Production runs were 1,000 a day. Forging dies failed after 1,500 pieces; therefore die cost was high. Including one secondary recessing operation which was done on a lathe, these parts were precision investment cast for one third less than the forged cost. Carbon was held to 0.07 per cent, which greatly aided the welding.

Saved Rolling Costs. Electrical parts were wanted in pure nickel. Contours were rectangular but with lengthwise bosses on top and bottom sides. To have rolled these out from solid stock would have been prohibitive in costs. Bars were precision investment cast with the necessary bosses. The bars then were rolled to final shape and surface finish, and cut off to length.

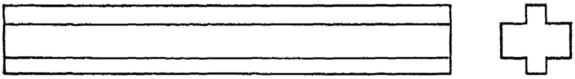


FIGURE 18. Nickel bars precision investment cast for rolling.

Gas Turbine Blades. The gas turbine blade is the most widely publicized application of precision investment casting; therefore very little discussion of it is needed in this text. Principal values contributed by the casting process as compared to forging are: ability to make some of the shapes at all, thinner trailing edges, quick production of experimental designs, higher strengths at high temperatures, controlled vibration-dampening abilities of the cast structure, and close control of carbon for high weldability when the blades are to be fastened in place by welding.

Chapter 3

Products Cast in Medium Quantities

Production runs of from 1,000 to 5,000 parts constitute at least 95 per cent of the number of orders received by precision investment casting shops, although not necessarily that percentage of the dollar volume of business. Big production runs, of course, account for large chunks of the dollar volume.

The reasons why precision investment castings are preferred for these medium-sized production lots are much the same as for the larger lots, as given in Chapter 2. But there is an important difference. The ability of the precision investment casting process to do in small lots what other processes can handle with economy only in much larger quantities is highly important in the instances in which that ability exists, and it exists in a great number of instances.

Tool costs also bring much of this medium lot business to precision investment casting. Very often, by ordinary fabricating methods, high-cost tools might be needed because it would be impossible to produce the item without them. Even though these costs could be absorbed in the prices charged for the product, they represent a capital investment which must be slowly amortized as the product is sold. They are a nuisance to store and to handle or set up, and there always is the danger that they may be destroyed by fire or broken by accident. Except in the rare cases where high-cost tools can give control of the market for a product because no competitor will bother to duplicate the production tooling, no manufacturer ever wants high-cost tools for low-quantity production. Precision investment casting often can work with comparatively low-cost tools.

Process *vs* process competition is different, too. In the large lot field, precision investment casting must compete against the fully automatic machine tool, the fully conveyorized sequence of production units. In the medium lot field the competition is more against the manually operated machine tools. In the large lot field this casting method must meet other processes at their highest efficiencies and lowest costs, but in the medium lot field it meets them at their highest versatilities.

Industry is in a trend toward the smaller lot, more versatile processes. Salt baths which can simultaneously heat-treat several lots of items with each lot requiring a different heat-treating time, welding processes which permit almost endless variations of major assemblies by varying their component parts, are examples of processes which are gaining in use because of their adaptabilities. Behind this trend is the fact that product designs are changing rapidly. New products and new variants of old ones must be developed with the least preparational and tooling costs. Obsolete models which are still in use by customers must have continued but diminishing supplies of repair parts; other obsolete models still enjoy sales demand from some merchandising outlets and must be supplied, but in diminishing quantities. All of these conditions require parts and finished items to be made by processes which are facile in their abilities to make changes. Precision investment casting not only is one of the most facile of those processes, but also it combines very well with others of them.

Some Illustrative Examples

Some examples of medium production lot items are:

Impellers for Stirring and Mixing Machinery. Impellers are "star"-shaped devices somewhat similar in form to the screw propellers of ships. Their use is growing in paper mills, chemicals industries, foods industries, molten salt baths, and other places in which liquid or even semi-plastic materials must be pumped, mixed

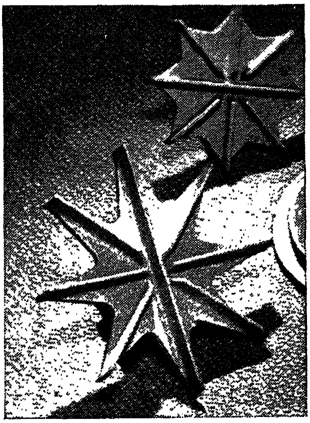


FIGURE 19. Impellers made by precision investment casting.

or kept at controlled temperatures. The exact forms, numbers and spacings of the blades must be carefully controlled. The design is in accordance with such hydrodynamic factors of the liquid as its viscosity, viscous shear, coefficient of friction, desired speed and volume of movement, and convection currents. Calculated also must be its abrasive and corrosive effects upon the impellers, its temperature and specific heat with consequent tendency to damage them by overheating, the tendency of its constituents to separate or to undergo undesired chemical changes if moved with certain forces or if not moved with other forces. Obviously, the contours of the impeller blades must be carefully designed and accurately made. Many of these impellers, therefore, are precision investment cast stainless steels, Monels, bronzes and other appropriate alloys. They commonly are fastened to the impeller shafts by welding or by brazing.

Latches and Keepers for Process Equipment. Process equipment such as tumbling barrels, high-speed centrifugals and the like, commonly has covers or other openable members which must be opened quickly and easily for loading and unloading of the equipment and for inspection of the work. The latches and their keepers must be tight and often must be wedge- or other compression-locking for secure closing. They must be quick-acting, safe for the hands and clothing of operators, hard for long wear, tough to resist hasty operation and mishandling, and corrosion resistant against any process or other materials which may get on them. Precision investment castings can provide the necessary alloys, contours and features at low prices and within the medium production lot ranges which generally apply to the sales of such process equipment. Two

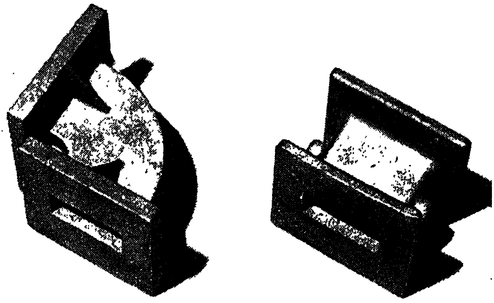


FIGURE 20. Latches and keepers are made in wide varieties of shapes, sizes and alloys.

usually are required per machine, one being left hand and the other right hand. Precision investment casting takes care of this variation with only minor increase in what the tooling costs would be if both were alike.

Minimizing of Inertia Loads. Feeler fingers coming into contact with the paper which passes through high speed automatic printing presses are difficult design studies in inertia and in static and dynamic balance. They must move so as to give signals to electrical control circuits, or to actuate control mechanisms, when the paper beneath them, or the absence of paper beneath them, allows their tips to move as little as 0.001 inch. The paper may be moving at speeds of over a mile a minute, or on other machines, at very slow speeds. Their movements other than those caused by the paper may be actuated by springs, by electric power, or by pneumatic devices. But the amount of power available to them usually must be little in order that it may be under highly sensitive control. Any inertia in the fingers themselves other than that which is wanted to control their actions, and any lack of the proper static and dynamic balance, must be compensated by power supplied to

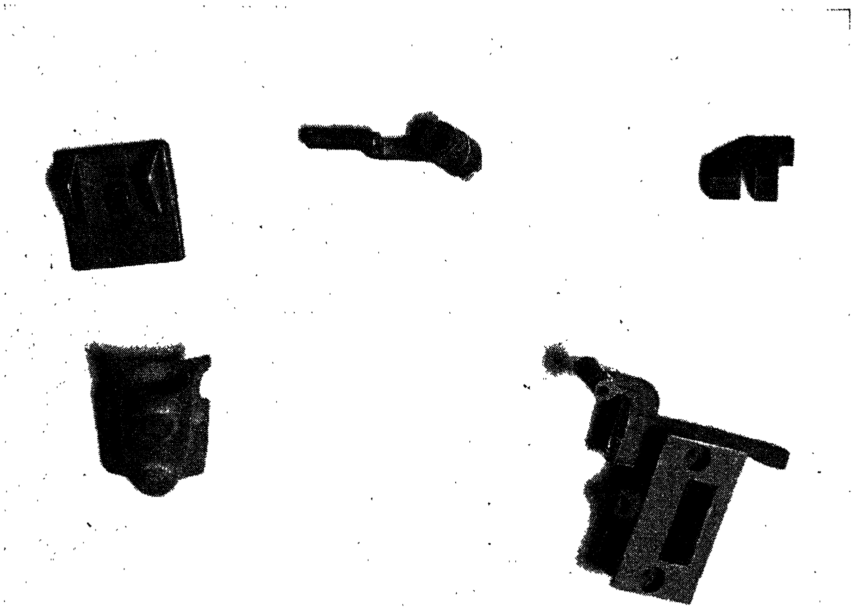


FIGURE 21. Small finely balanced parts are used on printing, vending, calculating, cloth making and dozens of other kinds of machines.

them and by lack of speed and of sensitivity in action. Paper is highly abrasive, and compensation for wear in such parts is difficult. Precision investment castings for these fingers are extremely hard and abrasion resistant as well as corrosion resistant. They do not need to be solid but can take advantage of deep channeling and other elimination of metal to reduce weight and its inertia. Their contours can be such as to provide ideal static and dynamic balance. And since relatively few models of the kinds of printing presses which use such fingers are designed to function exactly alike and to need fingers exactly alike, the ability of precision investment casting to supply these fingers in medium quantities with reasonable prices is highly important. As a rule a few drilling and other machining operations are needed to complete these fingers.

Similar parts are used on textile machines, coin vending machines, calculating machines and others.

Highly Intricate Chambering. An assembly used in radio mechanisms required highly intricate and accurate curved chambers and straight-walled chambers. With normal spoilage in assembling, these products could be fabricated for about $525.00 each by making various members separately and then brazing. By precision investment casting it was determined that these products could be made if the lowest dollar production unit was on the order of $30,000. That is, if 100 castings were wanted they would cost $300.00 each, and if 1,000 were wanted they could be had for about $30.00 each—that being the bottom limit to which the process could go at that time. Secondary machining operations included broaching, tapping and slitting after casting, and brought the price up to about $50.00 per finished product.

This is a reasonable illustration of what precision investment casting sometimes can do for assemblies which involve accurately contoured chambers and cavities with thin walls to be made of alloys which are difficult to fabricate. But these prices would not necessarily apply in today's markets. The abilities of brazing processes to meet problems have been greatly advanced, and so have those of precision investment casting. If made today the same product might be precision investment cast in subassembly form, brazed in final assembly, with further increases in contour intricacies and possible reductions of overall costs.

Elevated Temperature Parts. Mechanisms intended for elevated temperatures are not so common as those which are to operate at anything from room temperature to the temperatures common to high pressure steam. Therefore any valve wedges and other mechanical parts which are to operate at elevated temperatures usually are wanted only in moderate quantities. But the working stresses, the corrosive and the abrasive actions imposed upon those parts must be borne at elevated temperatures, and sometimes the parts also are subjected to the added thermal stresses of having some of their areas at drastically different temperatures than others. Alloys which will withstand these temperatures and other hardships commonly are very difficult to machine or to fabricate by any methods. Their contours must at once be suitable for their functions and designed to distribute the stresses to the areas which best can bear them. Their accuracies must be adequate, usually must be high. Precision investment casting can produce the necessary contours and accuracies in the most highly desirable alloys, at reasonable costs for the medium production runs needed, and with a minimum of difficult secondary or completing machining operations.

"Seasonal" Parts for Standard Machines. Machines used in style goods industries sometimes can be changed in accordance with the needs of their users by changing simple parts. An example is a cam ring used on such a machine. Machined from the solid this ring would cost $40.00 in lots of 1,000. Precision investment cast, and with a little machining as a secondary operation, the ring costs about $14.00 in the same quantities. At this lower price the invitation for the user to change over his machine for a style modification is much greater, the overall utility of the machine is greater accordingly, and more machines can be sold.

Surgical Tools and Appliances. Surgical clamps and other devices usually are wanted in highly varied sizes and contours but only limited quantities of any one item. Alloys of which they are made usually must be stainless steel or otherwise highly corrosion resistant, strong enough in thin sections so that failure in service is practically impossible, and with a controlled balance between stiffness in some areas and resiliency in others which gives them the indefinable quality called "correct feel." All of these requirements can be met very well by precision investment casting followed by suitable secondary operation heat-treating, polishing, assembling and adjusting. In one example surgical clamp parts were precision investment cast in 1,000 lots, the casting including one hinge slot which was held to limits of plus 0.001 inch minus 0.000 inch, with a net cost saving of more than $1.00 per instrument as compared to previous methods.

Molding Dies. Some dies made for molding cakes of soap, and for the kinds of plastics and other materials which are somewhat slow in cooling and solidifying, must be made in large enough quantities so that the mold injecting machine keeps in constant operation while a large number of filled molds are cooling to the temperatures at which their contents can be removed and the molds returned to the machine for refilling. When the internal contours of such molds are intricate enough and must be sharp or accurate enough to present a difficult engraving- or die-sinking problem, and the danger of rust or other corrosive attack is great enough so that the molds should be made of corrosion-resistant alloys which are difficult to fabricate, precision investment casting often proves to be the lowest cost process for making the molds. In several instances precision investment castings have saved enough on mold costs so that more molds of one model were made and the injection machines were stepped up to higher outputs, more variations of molds were made with consequent increases of the merchandise appeal of the molded products, and molds were retired from service when less worn with the result that the average quality of the molded product was improved.

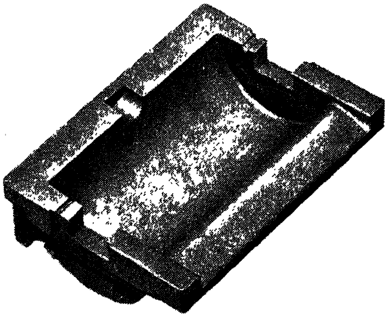


FIGURE 22. Molds are precision investment cast for plastics, rubbers and soaps.

Extrusion dies for hard rubber, for plastics and for soft metals, often are precision investment cast for these same general reasons.

Bottling Filling Nozzles. Nozzles for filling bottles in beverage plants and in foods plants formerly were machined of brass or else were made of steel and heavily galvanized. Precision investment cast of stainless steel, they are more easily cleanable, less corrodible, lighter in weight with consequent reduction of burden on the machine operating parts, and are lower in cost.

Chapter 4

Products Cast in Small Quantities

Products are precision investment cast in lots of 1 to 1,000 for much the same reasons that apply to very large quantities, as detailed in Chapter 2. But as is the case with medium quantities (described in Chapter 3), the ability of precision investment casting to suit the production run to actual needs can have highly important effects upon the amount of capital tied up in inventory.

One company which uses hundreds of different parts of intricate contours, for example, has long had a policy of calculating its inventories a year ahead. If the need for one part causes an automatic screw machine to be set up on 1-inch mild steel, round bar stock, the inventory cards are consulted to find the status of every item customarily made of that stock by that type of machine tool. A production run is arranged by which the machine first will run off a top inventory limit supply of the part immediately needed, then will have its tooling changed to run another part made of that stock, and then another until the top inventory for every such part is filled. This minimizes the automatic screw machine setup charges and allows automatic costs to be applied to parts which otherwise would need the higher manual lathe costs, but this is accomplished by having high amounts of working capital tied up in finished and semifinished materials inventory. The company is changing over to precision investment castings for many of its parts and has a long term program of this kind in the planning. By this process that inventory can be cut drastically, and with slight increases or even actual decreases in the costs per finished part.

Many other companies have this same problem with die castings, extrusions, forgings, small weldments, braze-assembled stampings, swaged parts, or with sand or "conventional" castings which need chucking lathe or other finishing operations that are costly for machine setups. Precision investment casting cannot invariably produce with economy in 100 or 500 lots where other processes need 5,000 lots. But in a great many instances, and especially when product designs can be modified to suit them to this process or to make use of the process features to improve the design or to eliminate assembly operations or secondary machining operations, precision investment casting can produce with economy in much smaller quantities than traditional processes.

Where small lots only are wanted, great care may be needed in the selection of the precision investment casting shop to make them. Some shops have continuous flow production lines, based on the use of steel molds and of special dispensable pattern materials injected under heavy pressures and of investment materials suitable for only limited ranges of alloys and of contours, and therefore are not interested in any production runs which do not fit these conditions. Other shops are highly adaptable. Some shops are owned or managed by companies which have specific metals or alloys for sale, and will take small production runs if the products tend to promote the sales of these raw materials. Other shops also have preferred alloys with which they do their best work, but have no secondary source of income which will cause them to welcome a small run if it is not profitable in itself.

Precision investment casting also has its experimental costs when working on a new product. And although it would be a foolish precision investment casting house which did not allocate at least 10 per cent of its gross income to research and development work for the improvement of its own techniques, if a small original production run requires heavy experimental costs, most of these costs must get into the price charged for the castings. Much of these original experimental costs can be avoided by intelligent decisions about what alloys the product should be made of, and what contours and dimensions should be produced by casting as compared to the costs of machining or other secondary operations. The bills can be high for sticking to whims, traditions or arbitrary decisions. When the test for alloys, dimensions and contours is "adequacy or superiority for the function of the product," precision investment casting is at its best for small lot business, or for business to be placed in any production lots, and so is every competing process.

Problems of product experimental development often can be relieved by precision investment casting. When a situation familiar to every experimenting engineer occurs, in which the performance trouble is so mysterious and imponderable that only trial and error can find and correct it, precision investment casting often can turn out several parts of slightly modified contours and dimensions and do so with lower costs and less delay than any other process. A highly adaptable casting house should be selected.

Toolroom problems are being solved in rapidly increasing numbers by precision investment casting. For example, when a highly intricate stamping is to be made, the toolmaker often cannot tell whether to begin with a 6-inch or a 9-inch blank until trial and error has told him. Such experimentation may take months of making up one die after another and then "winging" them (destroying them as failures) before the toolmaker finds himself on the right track. Precision investment casting cannot eliminate all of this trial and error, but it can provide semifinished tool shapes and parts and enable the toolmaker to make many more experiments in much less time. In addition to permitting him to vary the shapes and sizes and contours, it also can permit him to try various alloys. Product design experiments can be made by varying the tools.

Another vexatious toolroom problem is that of deciding whether to set up an expensive tool for high-speed operation or to hold it down to lower speeds with less chance of damage to the tool. If high-speed operation is selected, a single slight accident at the machine may cause tool damage which will wipe out years of profit on that operation. If slow speed is selected, the time of the machine and its operator and supervisor is less productive. Precision investment castings often can reduce the costs of intricate tools to such an extent that many duplicate tools can be kept available and the cost of breaking one by high-speed operation becomes only that of setting a new one up in the machine.

There are precision investment casting shops which are highly interested in this tool shape business, and shops which are not. Some of the most interested ones have staff metallurgists who like to think about tool alloy and shape problems.

Some Illustrative Examples

Some examples of small lot production are:

Single Stainless Steel Casting. This was to be a chambered part, overall dimensions about 5 by 3 by 3 inches, weight about 3 pounds. The engineering sheet showed that if made out of band-sawed sheet stock and silver-brazed for assembly, it would cost about $60.00; precision investment cast, it cost $25.00.

Special Ball Bearings. To withstand highly abrasive conditions a small lot of ball bearings having Stellite races and stainless steel spacers were wanted. Precision investment casting proved to be by far the most economical way of producing these parts, the races being cast as grooved blanks which then were ground in the usual way.

Medical Instrument Parts. Cystoscope parts were wanted in lots of 100. It cost $2.00 each to hog them out of bar stock, $1.00 each to precision investment cast them.

Form Milling Cutters. Form milling cutters were wanted for machining extremely hard and somewhat abrasive material. The operation was not such as to make carbide-tipped tools practical. Cutters made in the conventional way cost $92.00 each and would mill an average of 60 pieces before needing resharpening. Cutters, precision investment cast and then sharpened, would mill 25 or more pieces between resharpenings and cost only $6.00 each. Because there was no desire to have any more of these $92.00 tools in the tool crib than absolutely necessary, and there were the usual toolroom delays about getting them resharpened, there was a tendency for the machine operator to keep each cutter in service too long and to spoil work and tools accordingly. The precision investment cast cutters at $6.00 each were higher in outright economy, and their low cost permitted a much larger number to be kept on hand. The larger number made it practical always to have several sharpened ones at the production machine so that no dull tool would be used and less work would be spoiled, and also permitted the toolroom to make a production operation out of grinding several of them at one setup and thus greatly reduced the delays in getting them sharpened.

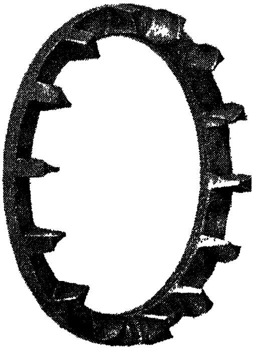


FIGURE 23. Special ball bearing retainers of wear- and corrosion-resistant alloys.

High speed cutters of many other types have been precision investment cast. Their production by this method ultimately will greatly reduce the costs of using specially shaped tools and will increase the economies of fabricating by machining.

Carbide and High-Speed Steel Tool Supports. Sintered carbide tool tips were to be used on the machining of an interrupted surface which was likely to set up destructive vibrations and break these expensive tips. The material to be cut was both hard and tough, therefore also prone to vibrate. Precision investment cast supports for these tool tips were selected because the cast structure metal is more dampening to vibrations than the wrought structure. The vibrations always occur at the sonic frequency of some member of the tool supporting structure or of some other part of the machine. By experimenting with contours of the various members, using high-speed steel tool tips for the experiments since these would be less likely to be broken by the vibrations, the vibrations were reduced to the point where they would be unlikely to injure the carbide tool tips.

For vibration-dampening contouring the tool supports needed to be chambered. These chambers in the precision investment castings were so formed that they could be used as feeding channels for the cutting oil, thus feeding the oil from beneath the tool tip as is desirable with carbide tool tips, and at the same time getting the usual flow tubes out of the way of the operator and the tools. The ability of the operator to watch his work was improved.

Precision investment casting supports, using the same design principles, were found to solve some of the cutting oil feeding and the chip breaking problems of high speed tool tips.

Dies for Plastics. Injection molds for plastics, made in small quantities, cost 20 per cent less than when made by other methods, and because of the superior alloys which it was practical to use in the precision investment castings, were found to have 30 per cent longer service lives.

Dies for Soles and Heels. Dies for the molding of rubber soles and heels had been made by die-sinking and engraving methods followed by nickel plating as a protection against corrosion. Their service lives were comparatively short, wear being caused by combined abrasion and corrosion. As an experiment, a few were made by precision investment casting methods, using a stainless steel alloy high in nickel content. These needed no sinking, plating or engraving; therefore they were much lower in first cost. It was expected that their lower first costs would be somewhat offset by reduced service lives. Their service lives proved to be so much longer that at the present writing no one knows how long they will last; they are refusing to wear out.

Die with Rapid Heat Conduction. Intricately-shaped metal pieces were simultaneously die cast and integrated with the threads of a fabric, thus eliminating a costly second operation of assembling and fastening the parts to the fabric. Original dies for the die casting were made of tool steel since the task of engraving them would be costly and it was considered wise to have a steel of the longest possible service life. This steel was sluggish as a heat conductor and did not always remove the heat rapidly enough to prevent scorching of the fabric. On the second lot of dies, precision investment castings were tried in order to secure their lower costs. These also were of a high endurance steel which was sluggish in its heat conduction. The same precision investment casting tools therefore were used to produce dies of a mild steel which is much higher in thermal conductivity. These eliminated the fabric-scorching problem and had highly satisfactory service lives.

Die with Intricate Boss in Female. It was desired to produce a flat-bottomed, cup-shaped stamping of a nonferrous and quickly work-hardening sheet metal. In the bottom of this, and projecting upward toward the mouth of the cup, would be a deep and intricately contoured indentation. The punch or male tool, therefore, would be male in so far as it forced the metal down into the female

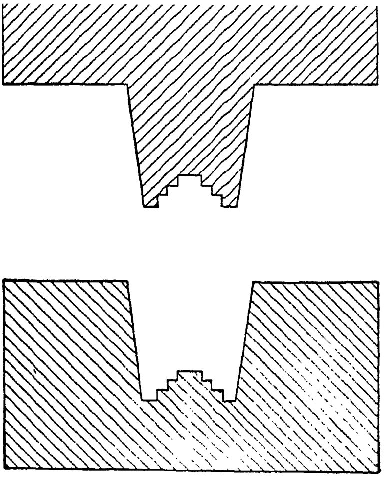


FIGURE 24. Schematic sketch of punch and die.

or die part, but would be female in that it would need a chamber in its end to receive the indentation. The female or die part, in turn, would have a boss or male part at its bottom to produce this indentation in the stamping.

Sinking this female die so as to produce the boss at its bottom would be a difficult operation although not an impractical one. But the normal way of developing this job would be to begin with a flat-ended punch and flat-bottomed die, draw the cup, anneal it, then transfer it to a second set of dies which would produce the indentation. Later on, when the exact shapes of male and female parts to produce the indentation had been worked out and proven in service, a main die would be made with the boss in the bottom of the female and the indentation in the end of the male and the stamping would be made in a single operation.

This costly two-step development stage was eliminated by the use of precision investment castings for the die parts. Male parts were cast with the necessary indentations in their ends, and females with the necessary bosses. The male parts were hardened and ground, then used for sinking the females, after which any necessary touching up was done, and the females were hardened and ground. Since the cost for these precision investment castings was low and several of them could be made for just about the same cost as one, experiments with the clearances and the other features obtained by grinding and other secondary methods could be made very inexpensively. And if slight modifications of original contours or dimensions were needed, modifications of the original castings could be had at even lower costs than those of the originals. Therefore the product design did not become static.

By such low-cost experimental methods, precision investment castings can "iron out" many of the imponderables which trouble the metal-stamping art and can greatly increase the use of stampings.

Spring-Tempered Novelties. Two hundred rust-resistant, spring-tempered novelty mechanisms were wanted as samples for investigating the sales potential of the item. The cost for cold-forming these from sheet stock would be $2,000 including die costs. Precision investment casting made the 200 samples for only $200. Cast of beryllium copper, they proved to have better spring qualities than were expected of the cold-formed products. Later on, if the products proved successful they would be stamped of sheet stock to reduce the costs on long runs.

Snap Gage Forms. By the usual custom these had been forged, drilled at the ends, fitted with the usual pins, then ground and lapped to size. Since economy called for the fewest different sizes of forging dies and therefore of forging sizes, adjustments for size were made by positioning and grinding the pins.

Precision investment cast forms could be made to the desired sizes, of extremely hard alloys, directly ground to size. This proved to be a stricter guarantee of accuracy of the inspected parts. And the overall costs were less than for the forgings and pins.

Plaster Extrusion Molds. Precision investment cast of Monel metal, plaster extrusion molds for making doll- and other novelty parts were lower in first cost and were longer-lived than when hobbed in steel and plated for rust protection.

Miscellaneous. Scale models of machines for saving shop layout time, special vise jaws, special thick members which are of low-carbon steel grades and spot weldable to large thin stampings, are other items which have been precision investment cast.

Chapter 5

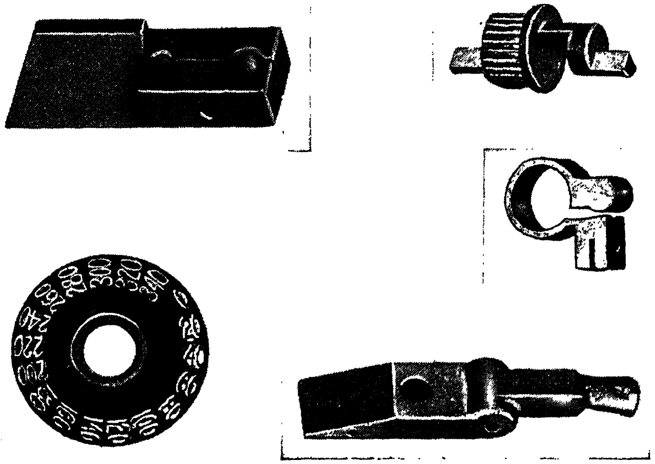
Economics of Design

Industry makes, uses and sells metal parts and products of millions of different contours, dimensions, accuracies, corrosion- and erosion resistances, strengths, resiliencies, stiffnesses, abilities to resist high and low temperatures, electrical and thermal conductances, surface appearances, weights, vibration-dampening or transferring abilities, and other properties, and of wide ranges of costs. To the extent that the properties and costs of any such item make it exactly suitable for its functions or uses, the design of that item is economical. Functional and cost suitabilities are the measures of design economies.

On this basis, very few designs even distantly approach complete economy. That is why at any given moment hundreds of thousands of designs are on the drafting boards for further study, and as many more are being studied by product-service testing facilities and by maintenance departments.

The reasons for lack of design economy are many. In a great many instances the factors which make for economy are unknown until some accidental discovery reveals them. An example of this is the ability of vibration-dampening properties in a part which has high-speed rotational or reciprocal motion to improve the performance not only of that part but also of bearings and other members which work with that part, some of which may be quite distant from it and apparently have little connection with it. Complicating this lack of knowledge is the fact that science is making only slow and plodding progress toward the measurement of vibration dampening, the effects of small increments of heat, the true definition and effects of viscosity, and other facts which the engineer needs to have presented to him in commercially simplified form.

All too often the facts are available but the designer, the merchandiser and the product buyer are satisfied with design expediency, with adequacy for the moment, when a truer approach to design economy would eliminate troubles, reduce costs and increase profits. This mental attitude can be caused by needing to ignore a minor problem while attacking a major one, and by habit or tradition. Whenever a new process causes designers and others to think more carefully about designs, thousands of these errors of expediency are eliminated. Precision investment casting is a process ideally suited to that purpose.



(Courtesy Arwood Precision Casting Corp., Brooklyn, N. Y.)

FIGURE 25. Designs like these are intricate for other production methods but easy and simple for precision investment casting.

Outright lack or high costs of raw materials can frustrate the best economies of designs. This lack seems destined to become worse as the sources of low-cost, high-grade iron ore and other materials approach exhaustion. The answers are in substitute materials with redesigns of parts to make them more suitable for those materials, and in the use of much stronger forms of present materials with product redesigns to make these forms least costly and most effective. Precision investment casting offers thousands of opportunities to use either of these stratagems or to use both in combinations.

Production equipment limitations also reduce the economies with which the product designer can work. The most common error of the newly trained engineer is to work out a highly imaginative, highly economical design which cannot be produced on any known equipment. Steels, brasses, raw materials of all kinds have been made with properties far below those which they could contribute to design economies, merely because with the higher properties they could not economically be fabricated on commonly existing machine tools. Thousands of parts and products have been designed with more weight than was wanted, and consequently thousands of tons of metals and alloys have been wasted, because fabricating equipment could not work with economy unless it machined away as little metal as possible. Precision investment casting is an opportunity to minimize or even to eliminate many of these fabricating problems. And in so doing, precision investment casting can put to use hundreds of design economy ideas which had been abandoned.

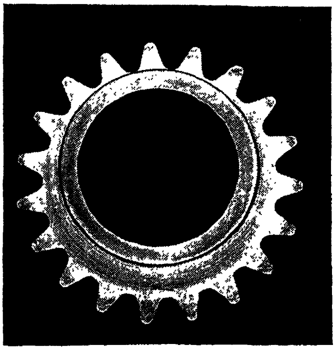


FIGURE 26. This eccentric sprocket has unusual contours but probably could be machined at lower cost than it could be cast.

(Courtesy Morse Chain Div., Borg-Warner Corp., Chicago, Ill.)

With all of these abilities, precision investment casting is not the "process to end processes." Metal stamping once was expected to end the need for nearly all metals-cutting machine tools, but instead of that it created thousands of products for which more and better metals-cutting tools were needed to make parts. Every known production method has had its turn at similar predictions. Precision investment casting sometimes is called "the method which will do to the lathe what the automobile did to the ox cart." Actually, as has been indicated in Chapter 4 and elsewhere in this book, precision investment casting is increasing the utility of every common process for the fabrication of metals and of the plastics and other materials which compete with metals.

Among the millions of parts and products designs there are a few thousands which will be most economical if made completely by precision investment casting methods, and several tens of thousands which will approach more closely complete design economy if made by precision investment casting plus secondary operations such as machining, heat-treating, grinding, finishing and welding.

The precision investment casting industry wants only its share of the business which will be created by considering product designs in terms of functions, costs, and economies. This same plea for functional design economy as the basis of judgment is made by the welding, the die-casting, the forging, and every other distinct industrial process industry. All such industries want the product to be designed to the highest functional economy first, then to be assigned to the process or sequence of processes most economical for its production, and finally to be modified in design so as to become even more economical for the selected processes.

The primary field for precision investment castings exists wherever certain factors are needed for product design economy and certain other factors are not. But since it will be a rare set of product functions which will dictate that one and only one process is best for making that product, it follows that any analysis of the functional design factors will only place the weight of evidence in favor of one process or another.

Asking the Design "Why?"

The method recommended for finding out whether or not a given part or product belongs to the precision investment casting process is likely to show that the product really should be a powder metallurgy part, a screw machine product, a forging, or the product of any other process. And no matter what the production process finally selected, this method is almost certain to result in a product of improved economy of design. The method is to go over every feature of the design and ask it "why."

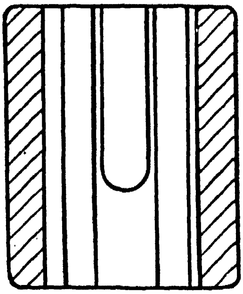


FIGURE 27. Blown up drawing of a tiny part.

The easiest procedure is to follow a sequence of steps.

Step 1. Blow the Drawing Up. The average part which might be precision investment cast is too small to be clearly visualized if drawn only to actual size, or even to double scale. The small drawing has too little space in which notes may be written and schematic improvement lines sketched in. These handicaps are made even worse by the fact that the average designer is unused to seeing *castings* drawings which are that small. Therefore a great deal of time can be saved by blowing the drawing up to five or even ten or twenty times its actual size. This can be done by photostating, or in many instances by free-hand sketching. A blown-up photograph of the part also is helpful. And when functional redesign or functional failure is hard to analyze, blown-up or oversize, but true scale models, have been used with great success.

Step 2. Why Those Thick Sections and All That Weight? Very few products have been designed with precision investment casting in mind. In most other processes it is less costly to produce thick and heavy sections than to eliminate metal and weight. This is absolutely true of any product machined from solid bar stock, plate or castings, and only somewhat less true of products machined from such "preformed" shapes as tubes, channels, other rolled shapes, and extrusions. It is somewhat, but only somewhat, less true of die castings and forgings. Whenever metal must be cut away to produce the desired contours and dimensions the cost of the cutting is in direct relation to the intricacies of the contours, the accuracies of the dimensions, and the amounts of metal which must be removed.

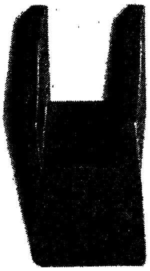


FIGURE 28. Precision investment casting finds it simple to eliminate metal and weight.

The heavy sections may be needed for stiffness to withstand chuck jaw pressures for machining, or wrench stresses for assembling operations. If so, it is quite possible that the precision investment casting process can eliminate the machining, and by combining two parts into a single casting, also eliminate the wrench operation.

Heavy sections may be needed because without them the part has insufficient strength. If so, precision investment casting may substitute a stiffer, stronger alloy, with little or no increase in cost.

Step 3. Why Those Truly Flat or Truly Cylindrical Surfaces? Solid bar, plate, sheet or tube stock usually has either truly round or truly flat surfaces. Ovals and other shapes can be had, but almost always at significantly higher prices. A great many surfaces are specified to be either round or flat merely because expensive machining operations ordinarily would be needed to make them a shape which would be better for the function of the product. Precision investment casting costs often are raised because surfaces are specified to be more truly cylindrical or plane than is needed.

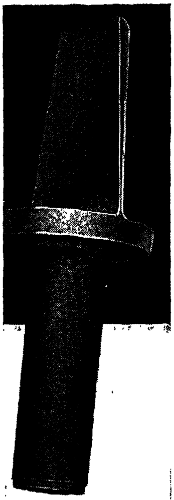
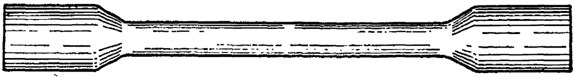


FIGURE 29. The intricately contoured blade can be a simpler high-precision casting problem than the more cylindrical shank.

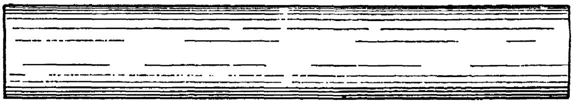
Other surfaces are round or flat because that is the way the usual machine-tool operation makes them. Any other contour always is produced at a slight increase in cost, whether it be generated by a form tool in a lathe, a formed milling cutter, the adjustment of a shaper head for each successive cut, or any other method. And in general, the more a generated contour has to be "off round" or "off flat" the more costly it is to machine. The temptation is, then, to stick to the truly cylindrical or flat unless the need for something else is strong. Precision investment casting has no such temptation, and can produce contours other than cylindrical or flat at no extra cost, even when their benefit to the product is only minor.

Step 4. Why Not Relieve Those Long Surfaces? Reliefs of long cylindrical or long flat surfaces can be among the most useful stratagems of product design. They reduce weight and avoid wastage of valuable metal, of course. And they add to beauty of design.

But beyond all that they can save much time along the product assembly line, and even more when machines must be disassembled and reassembled for servicing in the field, if two or more such items as ball bearings, gears, collars or couplings are to be mounted on the same shaft. Reliefs can provide extra room for wrench openings, lubricant storage, "reach through" welding or brazing operations, materials handling, the circulation of cooling air or fluids, the movements of tools for secondary machining.



relief section



straight section

FIGURE 30. When precision investment casting, the advantages of a relief may be had at lesser cost than that of a straight section.

When parts are to be through-hardened or case-hardened or otherwise heat-treated, reliefs mean that less weight goes into the furnace or the salt bath and that less heat and time and materials are used for accomplishing the same results. Reliefs often mean that instead of finishing a part all over for the sake of its appearance only the full size or unrelieved areas need be finished.

In spite of their possible advantages, reliefs often are avoided because the costs to produce them by machining are too high. They commonly require wide form tools, or long travel of single-point lathe tools, or extra milling or planing or shaping operations. But precision investment casting can provide them, usually with no extra cost, and very often at less cost than for unrelieved surfaces.

Step 5. Why Those True Right Angle Ends? When a piece of bar stock is cut off in a lathe or an automatic screw machine, or a casting is faced off, or anything is cut off with a circular saw or an abrasive disc or in most cases with a band saw, the cut goes straight across. Any contouring or profiling of the end is more costly, and with the exception of some shapes which may be generated with a band or friction saw at the original operation, almost always is done as a secondary operation requiring a second chucking. Drilling, with a possible follow-up chambering or counter-sinking operation, is one of the exceptions, but the machinist would rather not have to drill at the primary setup in a lathe or automatic if he reasonably can make a secondary operation in a drill press of this.

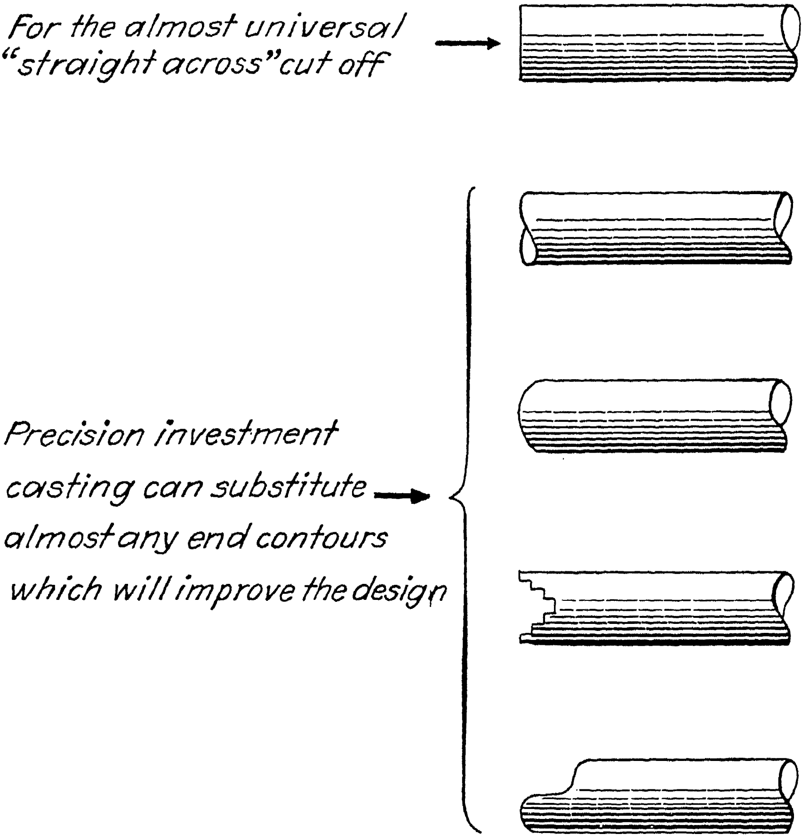

For the almost universal "straight across" cut off
Precision investment casting can substitute almost any end contours which will improve the design

Figure 31. Contour problems can be solved for designers.

Chamfering is another exception, but even this is bothersome enough so the machinist will turn it into mere corner breaking and do it in a tumbling barrel or a shot blast if he can. Trepanning, the cutting into the end surface at any other area than that of a drilled hole or the periphery, is one of the most completely avoided of all operations.

And if a lathe or an automatic screw machine can work on the exposed end of a bar or a casting, it certainly cannot do much with the end which is toward the chuck. Operations on this end almost always require that the piece be taken out, turned end for end and rechucked in another machine.

Plain square ends, or at best ends contoured in a single plane, as they can be contoured by a band saw or a flame cutter or by ganging in a miller or a shaper or a planer, are designed into thousands of products in which far more intricate contouring of the ends would greatly improve the functional design. Precision investment casting can produce those end contours, in both ends, usually at no extra cost or even with actual cost reduction.

Step 6. Why Those Blind Holes, Those Cylinder-Shaped Chambers? Drilling is a machining operation and costs money. The deeper the drilling, the greater the amount of metal drilled out, the greater the cost unless the stock is so thin that it would cost more to stop the drill before it got clear through. Many a hole, therefore, is designed to be blind when the product design would be functionally better if the hole went clear through.

Drilling, or some other method which generates a round hole or a circular trepanned groove or chamber, almost always is the least costly way of obtaining the chamber. Therefore most chambers are circular in shape. But many a product would be functionally more economical if the holes went clear through or if the chambers were of shapes other than circular. Precision investment casting can produce blind holes, through holes, or holes and chambers of any desired shapes. The shapes of the holes make little difference to this process.

Step 7. Why Holes of Just One Diameter, One Shape? Many a product would be better off if one or more of the holes in it were of two or more diameters or two or more shapes. But to drill one hole clear through or to some other depth, and then use that as a guide to drill another to a greater diameter but lesser depth, means a distinct stepping up in production cost. To machine out a chamber which is of two different shapes, as for example having a round

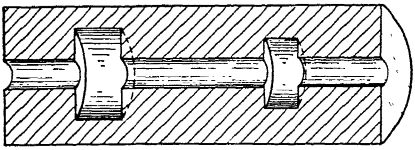
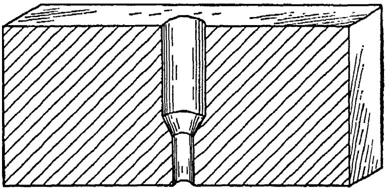


FIGURE 32. Precision investment casting produces interior reliefs or lubricant recesses at little extra cost.

hole at its bottom and a larger but square or hexagon hole at its top, means a drilling operation followed by a costly broaching one. And to machine out a hole or chamber which is small at its orifice or at both of its orifices, or at its orifice and its blind end, but is larger at an area beyond its orifice, can be a costly operation indeed. In fact, to machine out a chamber for anything but a very large hole diameter in which the inner diameter is to be larger than the orifice diameter, is so costly that in all but cases of extreme need it is avoided. The very countersinking of drilled holes is avoided.

Precision investment casting can produce all such holes, although for some of them its costs are higher per casting than they would be if different contours of holes were needed. But these extra costs rarely are great enough so that any real contribution to product design need be avoided because of them.

It can be less costly to drill a hole than to cast it in. But the precision investment casting process often can provide part of the shape, such as the hexagon area of a hole which is to be of two contours, or the countersink for a drilled hole, with no added cost for the casting and greatly reduced cost for the drilling.



Double diameter holes

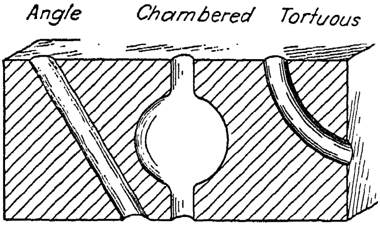


FIGURE 33. Holes intricate to drill are simple to cast.

Step 8. Why Are the Holes of Those Sizes, at Those Angles? A drill has to be started into metal, and once started it tends to deflect or "run out" in the direction of least resistance. The starting and run-out troubles are least if the drill meets the material at a true right angle. Therefore many a product is so drilled when it would be functionally better if the drilling were at some other angle.

The sizes of holes least costly to drill vary with the material, the thickness of section to be drilled, and the direction of the hole in relation to the surface. Many a hole is of a diameter not ideal for the product function merely because drilling becomes costly if the drill diameter be materially larger or smaller than the most easily drilled one.

At little or no extra cost precision investment casting can do several things about these drilling problems. Among its resources are:

(a) Provide holes which run in any desired directions. It even can produce holes which run in angled or tortuous direction if desired.

(b) Provide starting holes or indentations into which drills can be run, after which the drills if not of such small diameters as to be springy will follow true paths.

(c) Provide holes deeper than the true depths to be drilled, or provide through holes, but of diameters smaller than those desired, so that holes with true drill finishes but at the desired angles can be drilled with drills that mostly act as reamers.

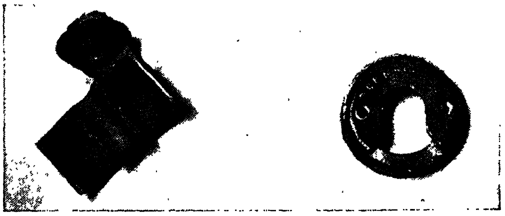


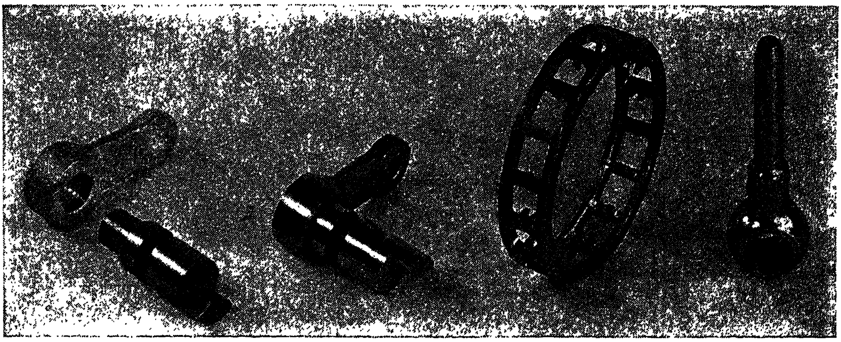
FIGURE 34. Holes and chambers can be as desired or as required.

(d) Provide bosses or indentations with flat faces, the faces to be at true right angles to the paths which the drills are to follow, so that the drill acts exactly as if it were at true right angles to the face of the work itself. These bosses later can be machined off if desired.

Step 9. Why Are Those Thin Sections Continuous with Thick Ones; Those Unrelieved Internal Angles Present? Precision investment casting is subject to slow cooling of its products; the investment is a good enough insulator to provide this. It is subject to controlled cooling since the invested flasks are small enough to be put into furnaces or into salt baths and cooled at any desired rates, although at costs per casting which are higher accordingly. Nevertheless it is a casting process and its products are liable to internal strains where more quickly cooling thin areas join slowly cooling heavy sections, or where there are internal angles unrelieved by fillets, or at any other "hot spots."

The designer's attention should emphatically be called to the fact that the strongest and most damaging residual or "locked up" stresses are built up after the metal has cooled below the plastic range at which it is able to flow in response to the gathering stresses. What is a hot spot for a casting also is a hot spot for any product which is to be heat-treated, welded, brazed, or submitted to any elevated temperature whatever.

The contours which become hot spots in heated objects are poor transferrers of operating stresses when those products are used at room temperatures. The fillets, gradual curves, ribs, thermal transfer members which prevent the formation of hot spots in castings and in weldments, also can be excellent stress distributors and vibration dampeners when the products are used at room temperatures, or at any other temperatures.



(Courtesy Kerr Mfg. Co., Detroit, Mich.)

FIGURE 35. Good casting design also is good functional design.

In short, unless absolutely unavoidable, unrelieved internal angles, abrupt junctures of thin with thick sections, and other hot spots, are thoroughly bad design no matter what the production method.

Many of these designs exist because by present production methods they are the least costly to fabricate. Precision investment casting almost always can eliminate such faults.

Step 10. Why Are Those Tolerances and Limits Necessary? Limits and tolerances are assigned for many reasons. Among them are:

(a) Really necessary for the function of the product.

(b) Shop habit. Every product is made to a class of limits and tolerances on every dimension, or every print is marked, for example, "plus or minus 0.002 inch unless otherwise specified," and then nothing ever is otherwise specified unless to closer tolerances.

(c) The shop lathes will turn to that accuracy if they machine the surface at all, therefore that accuracy might as well be specified.

(d) This is a chucking surface for subsequent operations, a control surface for accurate assembling, a reference surface for dimensional inspection.

(e) Accuracy is needed for assembling with other parts.

Tolerances and limits which are shop habits, or are those to which machines automatically will work, have no real meanings to the functional economies of products. If insisted upon, they can make the precision investment casting process valueless, and do the same thing for any process other than the one for which the part originally was designed. They are among the "whim costs" which are so destructive to industrial profits.

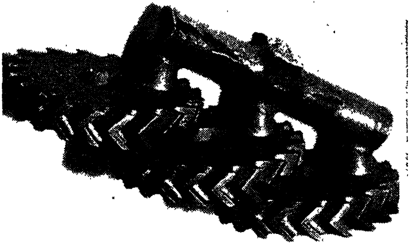


FIGURE 36. Herringbone gears rarely have tolerances closer than are functionally necessary.

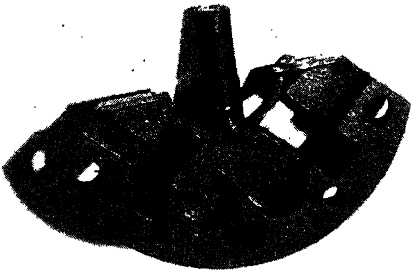


FIGURE 37. The slots had to be accurate and parallel to plus or minus 0.0005 inch. They were cast with a holding shroud which was machined away in the finishing operation.

Tolerances really necessary for the function of the product as at present designed, may be needed for dynamic or static balance, for maximum strength with least weight and sectional thickness, for proper functioning in relation to mating or contiguous parts. Sometimes precision investment casting can work to these tolerances and sometimes it cannot. But in a great many instances precision investment casting can substitute a stronger alloy, or permit a design of greater structural strength with still less weight, or otherwise eliminate the need for such close tolerances.

Tolerances needed for chucking surfaces or for other subsequent machine operations often can be eliminated when precision investment casting removes the need for that machining. If the designer will make all of his tolerances justify themselves he is likely to find that precision investment casting can give him, or can permit subsequent machining and grinding to give him, much closer tolerances on the surfaces and dimensions that really count. In exchange for this he may have to eliminate, or at least to widen, the tolerances which mean nothing to the functional economy of the product, or else pay a higher price than is necessary for his finished product.

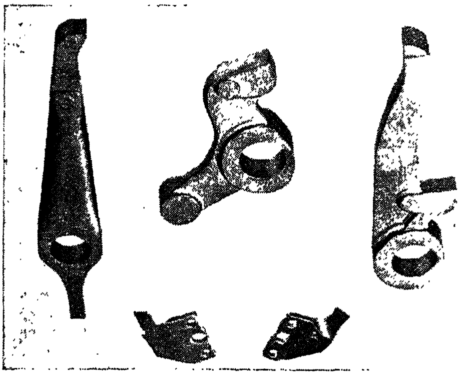


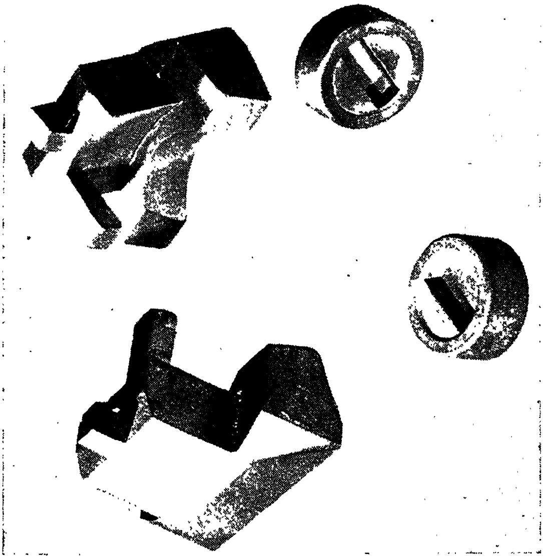
FIGURE 38. These knitting machine parts need precision dimensions only in the holes and at work contact surfaces. But they have precision contours for static and dynamic balance. The top three are SAE 4130 steel, the bottom two are Stellite.

(Courtesy Austenal Laboratories, Inc., New York, N. Y.)

Step 11. Why That Heat Treatment? If an alloy is not hard enough or does not have other physical qualities adequate for its purpose, it must be heat-treated. Sometimes the heat-treatment characteristically results in warpage or in other changes in contours and dimensions, or in bad surfaces, thus necessitating secondary corrective grinding and other operations. In some instances a different set of physical properties is wanted for one area than for another and the part may need to be case-hardened in one area and stopped off in another. The heat-treatment may result in superior resistance to corrosion. It may relieve residual stresses.

In other instances heat-treatment gets seriously in the way of joining or fastening methods. Heat-treated products rarely can be welded or even brazed without the beneficial effects of the heat-treatment being at least modified. Some of the highest cost stop off or other selective area heat-treating practices are necessitated by the problems of threading or of otherwise providing for fastening means after heat-treatment.

Precision investment castings very often can be made of alloys which for the purposes of the products involved can eliminate the heat-treatments. And where the heat-treatments still are necessary, these castings often can be made to such contours that the worst problems of the heat-treating are greatly reduced. Where present heat-treatments interfere with desired welding or brazing assembly methods, precision investment castings often can be made of metals which are inherently hard enough so they will retain all of the desired physical properties after those operations are complete.



(*Courtesy Austenal Laboratories, Inc., New York, N. Y.*)

FIGURE 39. The larger pieces are governor weights, 1020 steel, case-hardenable if desired. The smaller pieces are rayon seal parts, Nitralloy modified G. They are cast, nitrided, then lapped to size.

The ability of precision investment casting to work with special alloys to meet special conditions, and at costs which are surprisingly little if they are at all above those at which this process works with more common metals, never should be sold short.

Step 12. Why That Fastening or Assembly Method? Precision investment casting often can combine two or more parts into one. That is one of the primary resources which the designer ought to be considering as he studies that blown-up drawing which, it is assumed, he has made of the part for which this process might be used.

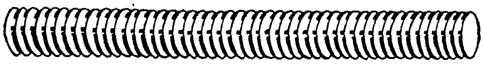
Every process, whether it be stamping, machining or what, has certain limits on the complexities of contours which it should try to produce. These limits vary with sizes of production runs and dimensions of parts and raw materials, and even with the shop equipment available to the product designer and his contractors. But the limits always exist.

Precision investment casting also has such limits. But in a large number of instances it can take two or more products that are at the complexity limits to which other processes ought to be required to produce, and can cast those items as one. Sometimes one of the items has been a screw machine product, another a stamping, another friction-sawed out of sheet or plate stock. If so the shapes to which they were fabricated almost certainly had to sacrifice something of functional economy in order to provide surfaces and means for joining. In combining them into one, precision investment casting may be able to eliminate these functional design compromises and result in a much better product.

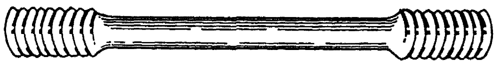
Where brazing or soldering or welding operations are desirable, precision investment casting can produce alloys especially suitable for them. The carbon and the alloying elements in precision investment castings can be controlled.

Quite often the areas to be threaded for assembly, or to be tapered, are selected because they are the only ones which can be machined from the solid for these purposes. Precision investment casting can provide wide varieties of special areas for threading, tapering, riveting, hooking or locking together, or other fastening means. The ability of this process to fabricate alloys which are especially strong or abrasion resistant for this purpose is highly important to the designer.

Threads, either tapered or straight, male or female, continuous or interrupted, and to any form such as USS or Whitworth, can be cast on precision investment casting sections. Only rarely can they be cast to closer than number 2 fits. Very often they can be cast to these fits and then improved in accuracy by chasing or by grinding. But they are more accurate as to diameter than as to length. And when considering them the designer usually should ask *"why is that threaded section so long?"* The lengths of threaded sections often are determined by the extent to which it is desired to have the female part extend over the male, since it is less costly to roll or machine a long thread than to relieve behind it and let the female cover the relieved section. But with precision investment casting this relieving is easy to do. Conversely the female hole can easily be cast to two diameters for relief and the female threaded section be made shorter, the relief diameter to come either before or after the threads or even to be on both sides of them.



Threading the whole length is easy for machining, difficult for precision investment casting.



Threading and relieving is easy for precision investment casting, difficult for machining.

FIGURE 40. If thread contours are to be cast the products should be designed for casting.

There are plenty of design resources which machining finds difficult to do but, within the limits of its thread accuracies, precision investment casting finds easy. Threading up to a shoulder with no relief between shoulder and threads is one of them. Producing threads of specially channeled contours so that lubricants may flow through them, or other "double service" be performed by them, is another.

Where threads are so long or so accurate that they should be cut rather than cast, precision investment casting still can provide these resources of specially relieved sections, specially chambered areas into which either the bolt head or else the nut can be fitted to hold it against turning, and the like. And the precision cast alloy can be specially selected for its workability under the selected threading tools.

Step 13. Why That Surface Finish? Surface finishes are selected for appearance, strength, corrosion- and abrasion resistance, and rarely for a wide list of unusual reasons such as providing a very thin but quickly wearable surface area which will assist a cutting tool or a bearing or other part to "break in"—to become especially adjusted to the peculiarities of the specific task to which its user assigns it.

The appearance of a surface can be specified in hundreds of finishes. Very rarely does the one selected have any valid superiority over a great number of others which might have been chosen. Precision investment castings are limited in the surfaces they can provide unless specially finished by secondary processes, and so are the products of any other process.

Surfaces contribute strength in that a superfinished (finished to accuracies measured in millionths of an inch) surface has fewer flaws or stress risers at which stresses will concentrate to instigate failures. Surfaces also may be peened or otherwise prestressed by work-hardening with resultant great increases in the strengths of parts. Case-hardening or other skin hardening can provide a rigid case over a tough and resilient core with high resultant strength for the product.

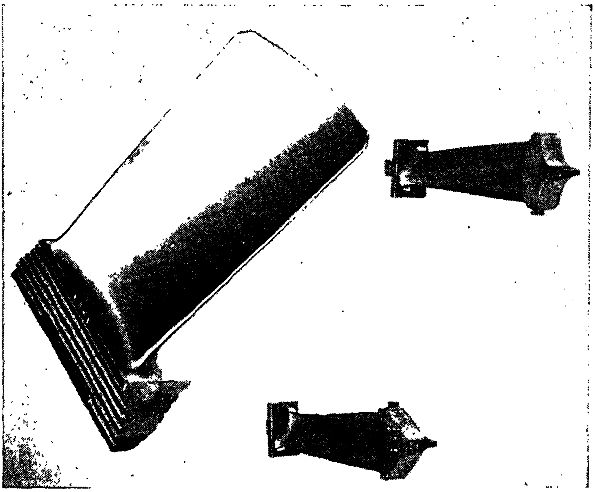
All of these resources are as open to precision investment castings as to any other products. But very often the need for special surfaces to obtain special strengths is inherent only in the present product design or the materials of which that design must be made by its present production method. There are thousands of instances in which an alloy and a design which could be handled by precision investment casting would eliminate the need for the high-cost special surfacing.

When surfaces are plated for corrosion- or erosion resistance, this operation sometimes can be eliminated by the use of precision investment cast stainless steels or other highly resistive alloys. And precision investment castings can be designed to shapes simple for plating, if plating is desired, thus in many instances greatly reducing the cost to plate.

The special effects, such as "break in" surfaces, "specially polishable" surfaces and "paint holding" surfaces, are obtained by various heat-treatments in salt baths, by dips in chemicals, and by special platings. The mere listing of them would require a thick volume. But the need for many of them can be eliminated by the use of precision investment cast alloys which do not need them for their purposes. And where they are needed, the careful selection of the alloy to be precision investment cast can minimize their costs while maximizing their effectiveness.

Step 14. Why Those Electrical Properties, Thermal Conductances, Vibration Transferring or Absorbing Abilities? In the fairly recent past metal products of the dimensions practical for precision investment casting rarely had more than two duties. They might withstand high temperatures with static loads but not also with dynamic loads, as for example, they might be used as furnace parts; but the high temperature gas turbine blade assignment had not come into existence. They might be required to withstand static loads while having desirable electrical properties but any vibration dampening was assigned to some other members of the assembly.

Today that situation is changing rapidly. The requirements of almost every mechanical product for higher strength for weight (high strength in proportion to weight) and of strength for bulk and weight are causing the changes. With these requirements are higher delivered or applied horsepower for weight and bulk, higher efficiency. These requirements are being met by higher rotational and reciprocal speeds for moving parts, higher operating temperatures, heavier stresses on parts which have smaller bulks and dimensions to bear them.



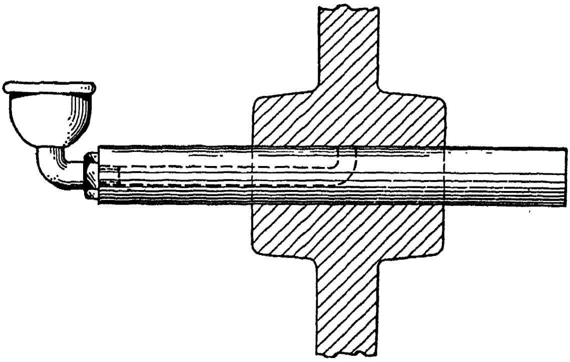
(Courtesy Austenal Laboratories, Inc., New York, N. Y.)

FIGURE 41. Precision investment cast turbine buckets have high strength for weight at high temperatures, plus high ability to dampen vibrations.

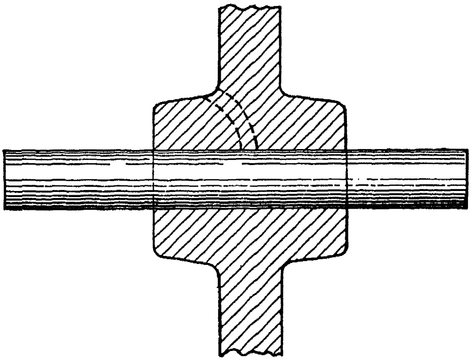
Important in this new scheme is the assignment of more duties, or more parts of the duties of whole assemblies, to single parts. Just one small part may be required to eliminate and inhibit and absorb high sonic frequency vibrations while bearing heavy dynamic stresses at high rotational speeds and conducting specific amounts of heat at high temperatures. The combinations of such duties are almost endless. And they tend to become more complex every time any designer finds out how to assign still more duties to a single part. The increases in duties may be drastic but they are more likely to be gradual. The high abilities of modern industrial products are mostly the cumulative results of thousands of slight improvements.

Abilities of metal products to assume more functions are dependent upon alloys, physical properties obtained with those alloys, contours, and accuracies. Precision investment casting is not the "be all and end all" in the solutions of these problems. But this process can make contributions which design engineers had not previously considered possible.

Step 15. Why Are Those Contiguous and Mating Parts Designed as They Are? A shaft had to be drilled to a depth of 3 inches



For a costly deep drilling task plus an oil cup.



Precision investment casting substituted an oil hole which follows a tortuous path. The cost was much less, the service better.

FIGURE 42.

from one end and then cross drilled to meet this hole in order to get oil to a bearing area 3 inches from the end of the shaft. This long hole was costly to drill, and whenever it became plugged with dirt or with sludge (the operation of the machine usually was careless) a difficult cleaning and maintenance problem was presented. By making a precision investment casting of the part carried by the shaft and providing within this part a lubricant passage which had to follow a tortuous path in order to be convenient for applying the oil can, the drilling of the shaft was eliminated. In some models of the machine a shaft large enough in diameter at the end which had been drilled so an oil passage readily could be cast into it, but stepped down beyond that point so the bearing diameter would be the same as in previous models, was precision investment cast and then machined at the bearing seat. Byt this latter means a lubricant passage was provided large enough so it was both easy to clean and unlikely to be clogged, and the cost of the drilling was eliminated.

A wheel-shaped part which carried a heavy thrust load at slow speed was difficult to lubricate at its thrust bearing surface. The hub member therefore was precision investment cast with a deep recess at the end, the recess being grooved to act as one race of a ball thrust bearing, a mating male member being precision investment cast to fit within the female chamber and act as the other race of the bearing. The female chamber was deep enough to overhang the male member and provide space for an oil seal, the alloys selected being hard enough for bearing race service but suitable for welding of the female member to its web and rim members which were friction-saw-cut out of hard steel. The male member was properly positioned and then tack welded to the shaft. Lubrication was needed only once a year.

The balances between functions carried by mating and contiguous parts can be varied in many different ways by making one or more of the members of precision investment castings. Many of these function assignments are made because, by traditional production methods, it is impractical to make one of the parts to such dimensions and contours that it will perform more of the functions. Precision investment castings can eliminate many such design compromises.

Chapter 6

Comparison with Other Processes

The average product or part for which precision investment casting is considered will originally have been designed for some other production process, or at least will have been designed by an engineer who is more accustomed to other processes. Methods for evaluating and changing designs to get the best from precision investment casting were suggested in Chapter 5. A general but fair comparison with other processes can give a second viewpoint on design transitions from one process to another. But the statement of Chapter 5 should be emphasized: that such comparison is as likely to assign a product to some other process as to precision investment casting.

Vs Die Casting

Die casting uses solid metal investments or "dies" which are used repeatedly for precision production of the same items. It requires well organized machine tools for the casting operation. A fair, low-limit cost for the dies alone is $1,500 for each product design to be cast. And this is only for the simplest of products. More complex products need more complex, higher-cost dies. The total cost to set up and operate can be high enough so that production runs of thousands or even hundreds of thousands of parts are needed to justify it. There are plenty of those runs and the die casting shops are making them.

Precision investment casting also has its equipment and its tooling costs. The costs to set up for precision investment casting are not invariably lower than those for die casting. And when tools costs are about equal, die casting gets out far more castings per average man hour than does precision investment casting.

There is a large field for die castings in which the present precision investment casting methods do not even hope to compete. This is where the largest dimension of the cast part is more than 7 inches, the contours and accuracies are such that the simplest of dies may be used, and the strength requirements are low enough to be suited to the alloys which die cast most readily.

One dividing line between the two processes is intricacy with accuracy of contours. As the intricacy becomes higher, the costs for die casting dies, generally, increase more rapidly than do those for precision investment casting tools. Therefore if the designer wants higher intricacy he either must have high enough production runs to justify higher-cost dies or else he might be better off with smaller runs and precision investment casting. Careful comparisons should be made on a product-by-product basis. Many designs are less economical than they might be because the designer does not realize

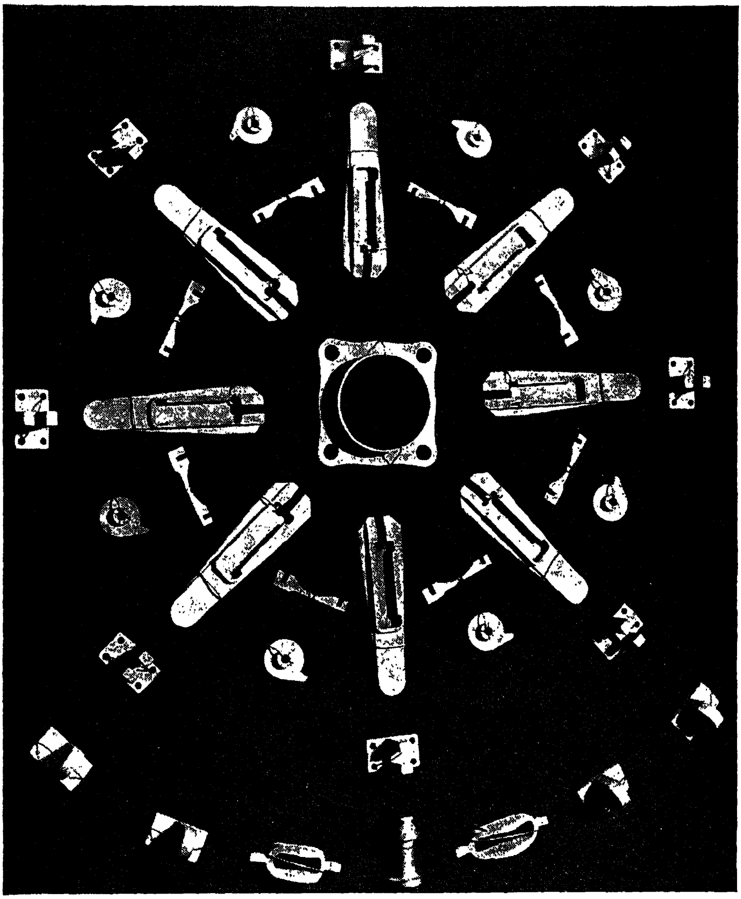


FIGURE 43. These parts are of alloys and to contours more suitable for precision investment casting than for die casting.

that precision investment casting can give him what he wants at tool costs that he is able to pay. Many intricate designs are worked out and proven in precision investment casting quantities and then transferred to die casting for lower costs on very large lots.

Die casting is capable of some design intricacies which precision investment casting is not. Die casting can cast one moving part within another and can cast inserts within main castings. It is very uncommon for precision investment casting to do either of these. They are possible but impractical for this process.

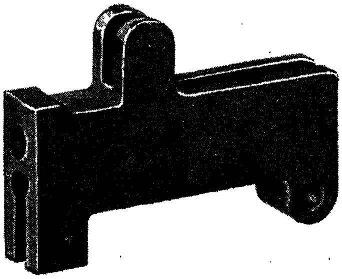
A sharper dividing line between the two processes is that of alloys. Die casting alloys are, in the main, limited to the nonferrous ones which are highly liquid and easy flowing. Precision investment casting, by contrast, can cast any alloy that can be cast at all. Very often a part is transferred to precision investment casting without any design change just to secure an alloy more serviceable for the function of the product. There are cases in which the same product is subject to various degrees of severity in service and some production lots of it are made at die casting prices for lighter duty and other runs at higher precision investment casting prices for heavier duty.

Die casting dies are worn or eroded or otherwise slowly injured by the metals they cast. This can mean that some areas wear and that the cast products become larger on those dimensions accordingly until die replacements or repairs are made. It also means ultimate destruction of the dies or of some of their working parts as useless for the part being cast.

The speed of this destruction depends largely upon the alloys cast, and is somewhat proportional to alloy melting points. Die service lives generally are longest with zinc alloys which melt at 700 to 725 degrees F, much shorter with aluminum alloys which melt at 1300 to 1400 degrees F, still shorter with the brass or bronze alloys which melt at 1550 to 1650 degrees F, and short indeed with the brass alloys which melt at 1700 to 1800 degrees F. Where these higher melting point alloys are needed, the precision investment casting process may be much lower on overall costs since this process is largely independent of the melting temperatures of the alloys it handles.

Die castings also are somewhat bothered by entrapped air. This is able to produce such weaknesses in the middles of solid sections that many metallurgists hesitate about recommending die castings for products which must bear critical dynamic stresses. Precision investment castings are not subject to this weakness and very often are preferred for critical services.

The die casting process has difficulty with any alloy which is subject to "hot shortness." Hot shortness is weakness at temperatures below the molten and plastic ones but above room temperature, the metal therefore being weak when it is hot but strong at its normal operating temperature. Such alloys are held against contraction by the steel die parts while cooling through their hot short temperature ranges, and in their weakened conditions are ruptured or seriously strained. Precision investment casting can provide investments which will be easily broken by the contracting metal and which therefore do not cause the metal to strain or fracture itself. More than one product for which a desirable alloy was abandoned because of hot-shortness trouble in die casting is now being precision investment cast.



(Courtesy Arwood Precision Casting Corp., Brooklyn, N. Y.)

FIGURE 44. This heat-treated aluminum bracket was die cast but was converted to precision investment casting for longer service life in the field.

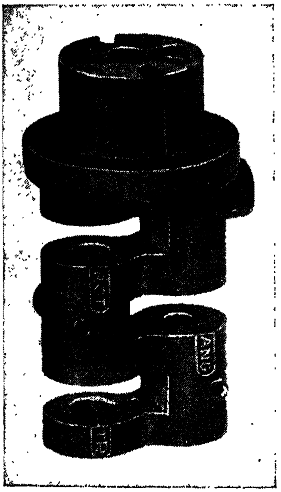
There are some aluminum and some copper alloys which are useful for either process and with which precision investment casting can obtain superior physical properties or can produce other better controlled results. Tensile strength increases of over 100 per cent, yield points and percentages of elongation to match, have been obtained by transferring the same alloy from die casting to precision investment casting. Dependent upon the service function of the product this may or may not have economical value.

Precision investment casting is an excellent method for producing die casting die parts and tools, and for making inserts for die castings. It is most often compared to die casting. The two are companion processes rather than rivals. They have just enough competitive overlap to join them firmly together.

Vs Screw Machine and Other Metals Cutting

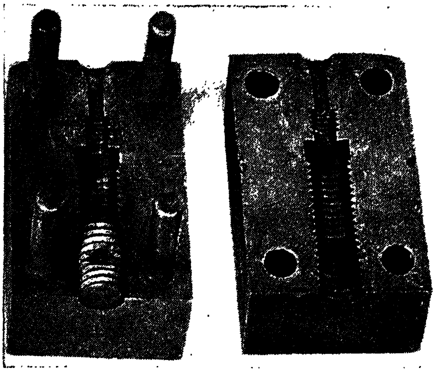
Screw machine products are the ones most often offered to the precision investment casting shops for quotations. The quotations very seldom win the business unless the product is to be modified or amplified in design or in materials to give it functional properties not generally obtainable by screw machine methods.

It must be remembered that the automatic screw machine is the end of a long series of operations which begin with the first melting of the alloy in the steel or other alloy mill. For the great bulk of screw machine operations every hot or cold step in the processing of that alloy is for the purpose of making it a better material for screw machine fabricating.



(*Courtesy Arwood Precision Casting Corp., Brooklyn, N. Y.*)

FIGURE 45. This microscope mechanism part (red brass) is screw machine size, but what screw machine operator wants to make it?



(*Courtesy Kerr Mfg. Co., Detroit, Mich.*)

FIGURE 46. Mold for external threaded part. In a highly machinable alloy this part should belong to the automatic screw machine. In an alloy of almost no machinability, precision investment casting is better.

The design features are exactly opposite to those needed for ideal precision investment casting. The screw machine wants to cut away as little metal as possible, to depend upon thick and heavy sections for strength, to work to high accuracy, to produce threads for the joining of parts, to depend upon secondary heat-treating operations if the parts need to be hardened or toughened for their service functions.

Precision investment casting by contrast prefers to eliminate metal and work to light sections, to depend upon alloys and contours and reinforcing sections for strength, to work to even higher accuracies in some respects but lower ones in others, to produce threads only very rarely for the joining of parts but rather to combine several parts into one or to go to low-cost brazing or welding, to depend upon secondary heat-treatments only if improved results cannot be had at equal or lower costs by the use of harder and tougher alloys.

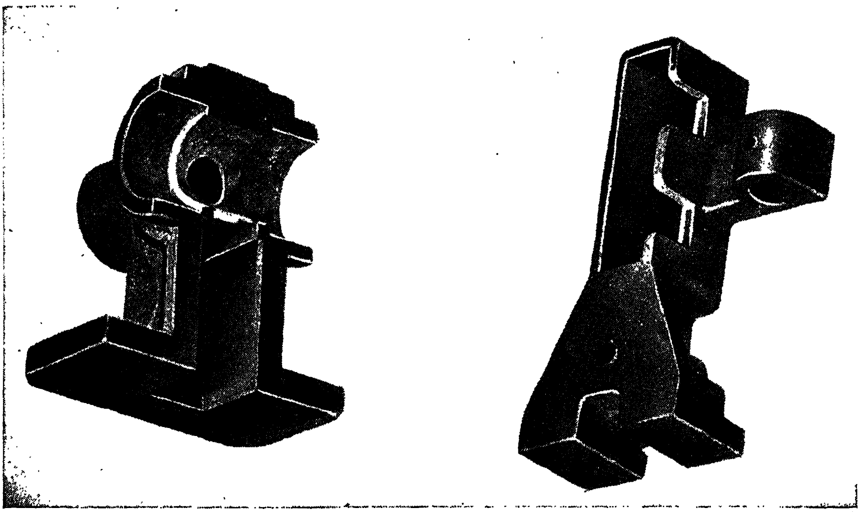
An outright screw machine product design can be taken over by precision investment casting when the part needs an alloy having properties not common to screw machine stock. Such an alloy might be harder, more corrosion resistant, more vibration dampening, different in specially balanced electrical or thermal properties, poor in machinability, and of too high cost to machine away as scrap.

Aside from that, the part must need, or must be improved by, design contours which the screw machine cannot readily produce, or else it belongs to the screw machine and not to the precision investment casting shop. The principal reason why so many screw machine products land on the desks of precision investment casting sales engineers for quotation is that the products of the two processes are of about the same physical dimensions and, on some dimensions, the same classes of accuracy. The two processes compete for the same sizes of parts, and for the right to make parts for the same functions, but not generally for the same designs.

Vs Sand Casting

Sand casting can make products several feet long on any dimension and weighing several tons; precision investment casting is limited to a few inches and a few pounds. The two compete only in a small corner of the sand casting field, and even in that field the sand casting price usually is much lower. There are some alloys, such as common gray iron, which often can be handled better by sand casting methods.

In its corner of the field, precision investment is far more able to produce intricate contours and accurate dimensions. It can handle with ease plenty of alloys which are impractical or even impossible for sand casting. Precision investment casting is an extension and not an invasion of the sand casting field. The precision process is much more comparable to die casting, to screw machine operation or to forging than to sand casting.



(*Courtesy Arwood Precision Casting Corp., Brooklyn, N. Y.*)

FIGURE 47. This sterling silver radar part and this bronze brush holder are of higher dimensional precision than can be had by sand casting.

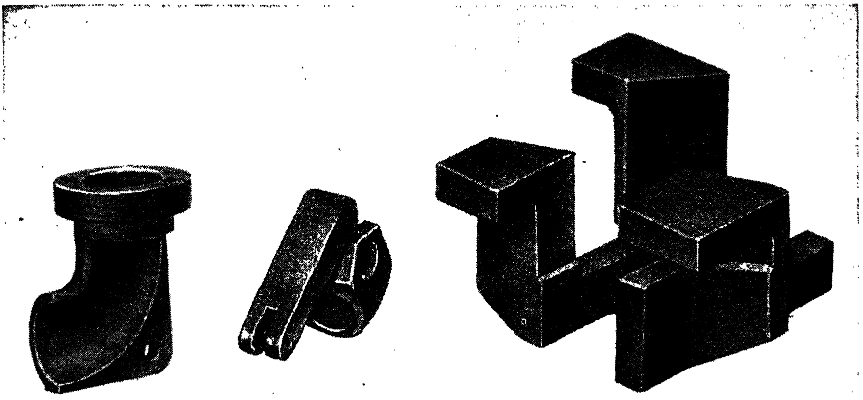
The product designer who has been using sand castings for products which might be made by precision investment casting, should submit the blueprint of the completely machined and finished product to the precision investment caster for quotation and not that of the original sand casting.

Vs Forging

As is the case with sand casting, forging gets the great bulk of its tonnage from products much larger and heavier than are practical for precision investment casting. Forging parallels precision investment casting in that both processes tend to develop the strongest alloys in the most strength-conferring or otherwise best functioning contours for their products rather than to obtain strength through weight and thickness of section. Precision investment casting will accomplish this to better advantage in some instances and will thereby take some business away from forging houses, but not enough to make a noticeable reduction in the forging business volume.

There is room for considerable detailed discussion as to whether forging can or cannot impart greater or better physical properties than precision investment casting in the cases of specific alloys used for certain products. Forging does "work" strengths into alloys, and in that working does control directional strengths to extents that precision investment casting does not. But forging generally works with metals which began as castings greatly inferior to some that precision investment casting can produce. Not all of these faults, or at least not all of them in all alloys, are corrected in all of the wrought process working steps, including the final forging ones. Forging can weaken some alloys, especially if performed under incorrect conditions. The extent to which either forging or precision investment casting can get the best from an alloy varies widely from shop to shop. But the physical properties obtainable by forging certainly are better known, especially to the average product designer.

Precision investment casting can work with far wider varieties of nearly all alloys. There are special "forging grades" of a great many alloys, grades which were specially tailored for forging from the first meltings of the metals in the mills. And with these somewhat limited grades the forge shop generally gets its best results.



(Courtesy Arwood Precision Casting Corp., Brooklyn, N. Y.)

FIGURE 48. These parts are wrong sizes, shapes and alloys for forging. But precision investment casting finds them simple.

Precision investment casting can, at an equal or even much lower tool cost, work to far wider varieties of contours and dimensions within the size limits of parts for which these industries compete. But forging is better off where thick and heavy sections are involved. The beneficial effects of the hammer can penetrate deeply.

Many forging operations are sequences of forgings, and the primary ones may be more difficult than the restrikes. Instances have been known, and undoubtedly will increase in number, in which precision investment casting has produced shapes ready for the final strikes of the last forging dies in the sequence. Precision investment casting also can be a profitable resource for some forging die shapes and parts and other tools.

Vs Stampings

Stampings, drawn shapes and "cold forgings" are made mostly of steels specially designed for them. And when their contours are intricate their tools are expensive, to be justified only by long runs. But in their proper field no other process can touch stampings for economy.

A high percentage of stampings are of larger sizes than are practical for precision investment casting. The overlap or competition between the two methods is not so slight as for sand castings or forgings, but is not major.

Several small stampings may be joined by soldering, brazing or welding to make one larger part. When this part is not too large it often may be replaced to advantage by a single precision investment casting.

When small stampings are to be subject to corrosive conditions or to abrasive wear they often must be made of materials much more difficult to fabricate than the ordinary sheet or strip "stamping steels," or else the stampings must be specially hardened or otherwise treated. Under these conditions precision investment castings sometimes can be substituted to advantage, especially if special design features not practical in the stampings may be incorporated in the castings.

Stampings are like precision investment castings in that they avoid thickness of sections and prefer to employ contouring of thin sections to obtain stiffness and strength. But the ability of the stamping process to do this at comparable tool cost does not approach that of precision investment casting unless very simple shapes will accomplish the purpose. And the ability of precision casting to make use of wide ranges of alloys having highly desirable properties is very much greater than that of stampings.

Precision investment casting already has done much to reduce the tools costs of stampings and is destined to do a great deal more. See Chapter 4.

Vs Weldments and Brazed and Soldered Assemblies

A product which has members joined by welding is a weldment. Makers of brazed and soldered assemblies have not gotten around to calling their products "brazements" and "solderments" but for the sake of simplicity in technical discussions they logically should.

These three processes share one philosophy of design with precision investment casting. All four take over when one of the simple processes such as stamping or machining finds the contours of a product too complex to be made at low cost or even to be made at all. But whereas precision investment casting is likely to displace completely the original machining or other process and to produce the entire product by its own methods, the "heat joining" processes of welding, brazing, and soldering move in as allies of the original process and take over some of its troubles.

All three heat joining processes are capable of producing products of much greater weights and dimensions than are practical for precision investment casting and therefore the fields within which this process competes with them is limited. But in the field of smaller assemblies the heat joining processes are at their highest efficiencies. They can use their most effective mechanized and automatized equipment, their lowest cost materials. Their process troubles are fewest.

Especially for these smaller products but also for some of the larger ones, welding long has had the spot, compression, projection, flash, seam, flame machine, flame compression, pulsation and other high-speed, low-cost processes, and now is coming along rapidly with the automatic and semi-automatic arc. Brazing and soldering began with the ganging of parts in multiple fixtures for torch methods, went on with the hydrogen and other controlled atmosphere muffle furnaces through which assemblies were fed in mass lots, and is making enormous strides with the newer methods of radiant gas, induction heating, and salt baths. Assisting with all this are the newer methods of preparing contoured shapes for heat joining, the friction sawing, automatic flame cutting, rolling and extruding as well as rapid advances in bending and other forming equipment.

The new developments in clad metals, such as a thin layer of stainless steel firmly bonded to a much thicker layer of lower cost carbon steel, depend very largely upon heat joining methods for the assembling of their end products, and are contributions to the heat joining arts. Heat joined products can make use of plating, of hard surfacing by welding deposition of metals, and of metals spraying, where they need extra surface protection to resist corrosion and abrasion. And altogether, the competition between heat joining and precision investment casting for the same small products assignments is going to be very interesting to watch.

Welding is far more successful with some alloys, and with some modifications of various alloys, than with others. This is so true that the ability of an alloy to be welded readily is called its "weldability" and weldabilities will be the subjects of high cost and extensive research for many years to come. There are "weldable" grades which are to be preferred for weldments in a great many alloys. Ferrous alloys high in carbon and therefore in hardenability by heat-treating, for example, generally are not among the weldable grades. Whenever an alloy of a less weldable grade would be economically beneficial for a product, the abilities of precision investment casting to produce the desired part in that alloy or even in an alloy highly superior for the purpose should be investigated.

In thousands of instances welding escapes its "weldability troubles" by the use of special alloys in welding rods, by brazing or otherwise metal-coating the surfaces of the parts or, in the case of welding some of the dissimilar metals together, metal coating one of the surfaces, and then welding these especially prepared surfaces together. Welding also overcomes some weldability problems by the use of high-cost, highly controllable electrical and other equipment. Sometimes these stratagems result in weldments of lower strengths, corrosion- or abrasion resistances, impaired appearances, seriously elevated costs, or otherwise reduced values. In such instances precision investment casting may produce a functionally superior product, may restore or even increase the values. The point is that the designer neither should weld for the sake of welding nor cast for the sake of casting.

Brazing and soldering have an extremely wide list of braze alloys and solder alloys which can be used for joining parts made of various alloys, and are much less subject to limitations in their abilities to join successfully. But in most instances, although by no means in all instances, the strengths and the other endurance abilities of the joint are in direct proportion to the temperature required for making it. Brazing generally is not as strong as higher temperature welding; lower temperature brazing (the temperatures are fixed by the performances of the braze alloys or solder alloys) is weaker than higher temperature; and low temperature soldering with lead-tin solder alloys is weaker than any brazing. The designer should pay no attention to these gradations of strength unless they make functional differences to the economy of his product. But in a great many instances the best way to solve these strength and other endurance ability problems is to make the entire product a single precision investment casting.

Precision welding, brazing and soldering often require the use of highly organized machines and tools, some of which are useless except for the product for which they originally were designed. When this is the case, a precision investment casting may deliver a product of equal or greater value at a tools cost so much lower that the production lots must be very large indeed before the heat joining operation can be justified.

Welding, and to a lesser extent brazing, can develop thermal stress problems which are highly similar to those of casting (see Chapter 5). But the welding applies the heat to only limited areas or "weld zones," and in these areas all the plastic deformation which accompanies the contraction of the cooling metals must take place. Stresses sufficient to weaken seriously the weldment can be formed when the weld zones have cooled below their plastic ranges but still are contracting. The stresses are not necessarily concentrated at the weld zone but may be distributed or even may be set up in various areas of the weldment. And when the weldment is of the multiple member and complex structure type against which precision investment casting ordinarily would compete, these stresses and their resultant strains may be so complex that no mathematical science is able to analyze and calculate them.

Avoidance of such stresses may dictate that the weldment be of less than ideal design economy. Relief of the stresses ordinarily is done by heat-treatment, by annealing at subcritical temperatures. In permitting the stresses to escape, the heat-weakened material may strain, warp or deform to such an extent that costly corrective operations must be performed. The alternative to this may be annealing in fixtures, which in itself can be costly. Precision investment castings themselves go through this same stress-relieving procedure, but they begin it when the metals first are poured, continue it as the metal cools to the plastic and from that to the solid, and if needed their cooling rates can be so controlled that no section cools significantly more rapidly than any other, thus obtaining a cooling condition which permits only very low stresses to form.

Welding also can be done with the entire assembly heated to at least its plastic temperature and then cooled very slowly, but only, for most weldments, at fairly high costs.

When the product design is complex enough and the accuracy requirements high enough so that the stress-relieving of a weldment or of a brazed assembly becomes costly, that product almost certainly can be made to better advantage by precision investment casting, provided of course that its dimensions are within the range practical for this process.

Precision investment casting can provide parts which are of metals and of shapes ideal for welding, brazing and soldering. Many a small product design can be vastly increased in functional economy by combining the casting and heat joining processes.

Precision investment castings also are used as members of very large weldments. They may be cast to highly intricate and accurate shapes and then welded to the ends of rods, of tubes, or to other surfaces. Similarly, precision investment castings may be brazed or soldered to very large assemblies, or to smaller ones. A great deal of this is being done in the making of tools and in the applying of specially corrosion- and abrasion-resistant areas and devices to various assemblies.

Precision investment casting can be an ideal method for making parts which are to be brazed by furnace, induction heating or salt bath methods. Often these parts need special contours in order to provide areas which will hold the braze or solder alloy mechanically until it flows, or which will permit the parts to be held by light press fits and so avoid the use of fixtures until the alloy can flow, and for other purposes. Precision investment casting can be ideal for providing these contours at the required accuracies.

Precision investment casting also will lend itself to types of thick section projection welding which have not generally come into use. Projection welding depends upon projecting areas or bosses which extend from one weldment member toward the other. The two members are brought together so that these bosses contact a flat surface; electrical current is applied; the high resistance at these narrow contact areas generates high temperature over a local region and makes the projections plastic; the application of pressure forces the members together and completes the weld. This is easy to do when the members are of thin sections and the bosses or projections can be stamped. Producing them by precision investment casting throws the projection welding process wide open to much thicker sections.

Precision investment casting is an excellent method for producing wide varieties of tools and tool parts for welding, brazing and soldering operations. It can produce fixtures, jigs, clamps, wheels, electrodes, guides, knock outs. Many operations have been slowed down or even abandoned because, as made by other processes, these tool parts are too costly as compared to their relatively short service lives. Precision investment casting of special alloys may reduce those costs while increasing operating efficiencies and prolonging service lives.

Heat joining processes and precision investment castings will compete very interestingly over narrow segments of their respective fields, and will combine just as interestingly. Together, they offer the designer tremendous opportunities for removing functional economical limitations from his designs.

Vs Powder Metallurgy

Powder metallurgy and precision investment casting often are compared to each other, mostly on the basis that any two new processes making parts of about the same dimensions would be pitted against each other in the minds of the designers.

Actually, the field of competition between them appears to be very narrow. Both depend upon close metallurgical control as one of their principal virtues, but the metallurgical results rarely are of overlapping properties. Powder metallurgy appears to produce porous structures to much greater advantage, although the abilities of precision investment casting to make products of controlled porosities should not be disregarded. Precision investment casting appears to be capable of far wider ranges of hardnesses and softnesses, stiffnesses and resiliencies in the metals it can fabricate. But both processes are developing so rapidly that no limitation placed on either of them right now would be sure to apply a year from now.

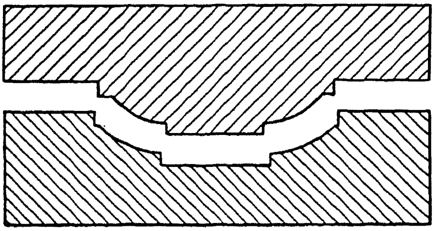
Powder metallurgy can be less costly for products of such contours that they can be pressed into dies and removed from them. On some classes of contours it can achieve higher accuracies. It cannot, at this stage of its development, work to anything like the contour intricacies practical for precision investment casting. Very few designs are equally suited to both processes.

Precision investment casting is an excellent resource for making some of the tool and died parts needed by the powder metallurgy shops.

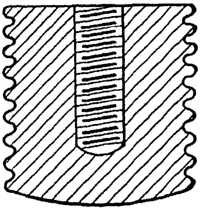
Vs Plastics

When plastics in any of their dozens of kinds are suitable for a product they usually are so much lower in cost and higher in economy that it is difficult to imagine precision investment casting competing with them for the same assignments.

Precision investment casting is likely to gain far more business volume by making tools for plastics than it will lose by losing product designs to them. Some plastics must have such long "dwell" or "setting" time periods in their molds that, for products requiring thick sections and consequently long dwell times, they have been abandoned because it was impractical to produce enough molds so that a great many filled molds could be dwelling while the plastics machines were filling others. Precision investment casting can provide these molds, and for plastics products of intricate contours, at costs never before approached by the plastics industry (see Chapter 4).



Precision investment cast molds for plastics can be of more durable alloys than ordinarily would be machined.



Inserts for plastics can be precision cast of corrosion resistant alloys.

FIGURE 49.

Some plastics are highly abrasive to tools. Those containing glass fibers are an example. For these the ability of precision investment casting to provide molds and other tools of metals extremely resistant to abrasion, and to provide them at very low replacement costs, can make the difference between profit and loss on some plastics products. Other plastics will chemically attack metals, but precision investment casting can make tools of resistant metals. The specific heats and the thermal transferabilities of the tools can be important, and these properties also can be controlled by alloys, tools section thicknesses and contours which precision investment casting can fabricate. The tooling-up of the plastics industry will enter a new era when precision investment casting is fully applied to it.

Inserts and other reinforcements for plastics products can be made to great advantage by precision investment casting. The plastics industry eventually will take precision investment cast deeply and intricately contoured parts, inject them with plastics which will be held fast in the chambers and will be exposed at some surfaces while the metals make up the remainder of the surfaces and contribute the physical strength, and thus will develop products for everything from jewelry to electrical equipment and precision instruments.

Vs Other Fabrication Methods

Every common fabrication method, such as rolling, extruding, spinning, drawing through dies, has wide fields in which it does not compete with precision investment casting, and narrow fields in which it does. And within the field of competition every such process has some products so ideally suited to it that precision investment casting never could offer serious competition, and neither could any other process. But when any process needs costly tools for other than large quantity output, or cannot readily fabricate alloys having the ideal properties for the product, or requires high-cost machining or welding or heat-treating or other secondary operations for the completion of the product, there is an excellent chance that the product will be more economical and profitable if redesigned for precision investment casting. But in many instances precision investment casting can reduce tools costs or make more intricate tooling applicable and solve the problem in that way.

It is very rare for any new production method to completely displace an older one in any field, or to do more than take over the products which the older method handled only with difficulty. The new method usually builds a field of its own. And that is what precision investment casting is doing.

Chapter 7

Metals and Alloys

There are a few alloys which form such bad surfaces, no matter how they are formed, that they must be cast into ingot molds and their entire surfaces machined away, after which the ingots must be reduced to the desired shapes by rolling and other wrought methods. Aside from those few, any alloy which can be cast at all can be precision investment cast. Some alloys not previously considered castable are precision investment cast.

Castability. "Castability" is a term easy to understand but almost impossible to define completely. It means more than "ability to be so poured into a mold that the alloy will solidify to contours similar to those of the mold interior." It means "ability to be cast by economical means into shapes which have all of the desired dimensions, accuracies, contours, and physical and chemical properties." In short, castability is the ability of an alloy to be made into castings which give the designer what he wants, at an economical cost.

By that criterion more alloys, and more modifications or gradations of alloys, are castable by the precision investment casting method than by any other known process. But in common with die casting and other highly controlled casting methods, precision investment casting faces an even stiffer requirement.

Most castings, and especially most sand castings, are mere raw materials which are to be fabricated to final contours, dimensions and accuracies by machining, or are to be improved in metallurgical and other properties by such steel mill and other alloy mill practices as hot and cold rolling and drawing. Cast by the more common methods, alloys need only be castable into castings suitable for use as raw materials.

Highly controlled casting processes such as precision investment casting, by contrast, must produce castings suitable for use as end products with few or no completing operations. Castability then becomes the ability of an alloy to be made into castings which give the designer the *final* product he wants, at an economical cost, with few or no operations subsequent to the casting one and intended to improve the dimensional accuracies, the contours, or the physical or chemical properties of the castings. In short, castability becomes the ability to cast an alloy economically into a product of the final shapes and qualities the designer wants.

By this extremely exacting criterion even more than by the simpler raw materials one, more alloys and more modifications or gradations of alloys are castable by precision investment casting than by any other known process.

A middle ground exists between those extremes of "as raw materials castability" and "as end products castability." This ground is that of castings which still might be regarded as raw materials but are much closer to the end product stage and are to be completed into end products by relatively fewer operations than are other castings.

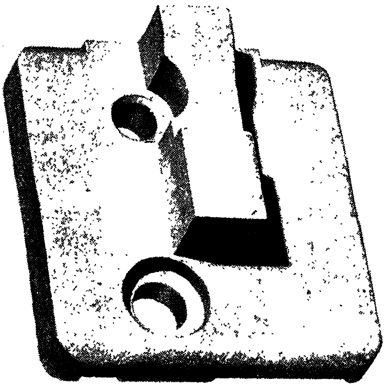


FIGURE 50. This paper container machine "sled" is of SAE 4140 steel, readily induction hardenable on selected areas.

(Courtesy Austenal Laboratories, Inc., New York, N. Y.)

An uncommon but rapidly increasing form of this middle ground is that of castings which need hot and cold working to achieve the physical and chemical properties needed in the end products but are of such alloys that doing such work on the extremely large masses of metal common to steel and other alloy mills is impractical. In one example of this, rods were wanted for fabrication in automatic screw machines. The needed alloy, even if raised to a temperature just below that at which it would melt, still was too hard to be rolled in the large billets common to steel mill practice. The conditions were even more difficult because to avoid unnecessary machining of this hard and high cost alloy the rods were wanted in "contoured" rather than truly round, square or hexagon cross sections. Pieces of the necessary contours and about 18 inches long were precision investment cast, but with cross sections somewhat larger than those finally wanted. These pieces were hot rolled in specially contoured rollers. Because of the relatively thin original cross sections, the physical effects of the rolling were produced throughout the cross sections. The processes and results were exactly like those which would have existed if an alloys mill had been able to take large billets, progressively roll and draw them down to much thinner bars, and finally form-roll these bars to the desired contours.

By these "middle ground" criteria, precision investment casting also provides castability for more alloys and more modifications and gradations of alloys than does any other casting method.

The Controlled Properties of Alloys

Most of the alloys in common use are specifically intended to be machined, stamped, die cast, welded or fabricated by some other definite method. The alloys mills which make them rarely can run 100 per cent virgin metal but also must include scrap in the melts. The scrap rarely is completely controllable in its ingredients and the ingredients are not always entirely known; alloys mills often find surprise ingredients. Minute quantities of surprise ingredients can have very large good or bad effects. Extremely small variations of the proportions of the intended ingredients can have astonishingly large effects upon the ways in which the alloy behaves when being fabricated on the product production line (the fabricatability of the alloy) and upon its values in the end product. Therefore the alloys makers and fabricators commonly specify min-max (minimum and maximum) proportions of the intended ingredients and amounts of the surprise ones.

These min-max specifications are the products of laboratory research and of practical experience. They are such that the alloys mills can achieve them while melting in extremely large quantities, and if the alloys are not to be shipped in pigs as for die casting, the mills can further control properties by varying the annealing and other heat-treating, and the rolling and drawing and other hot-working operations. The fabricators in turn can vary their operations in accordance with slight variations in the fabricatabilities of the alloys.

The net result has been a wide list of standard alloys in standard lengths and cross sections, suitable for use in any well-equipped fabricating shop, made with the economies of large production quantities but purchasable in small lots, able by variation of fabricating processes to be made into end products of widely varied and highly controlled physical and chemical properties. Added to these are special alloys available to automobile makers and other fabricators which use large enough lots to warrant special meltings or "heats." The system does not work perfectly, as can be learned by listening to the troubles of any alloy products sales engineer. But it does work well enough to permit the fabricating of millions of highly economical and highly satisfactory end products.

Not the least of the satisfaction with this system is in the fact that industry is thoroughly accustomed to it and that it has resulted in highly satisfactory standards of alloys which may be specified for standard end products.

Suitability for the Purposes. The alloy as delivered to the fabricator has to have two distinct types of suitability: (1) suitability for one or for a sequence of fabricating processes; (2) "as fabricated" suitability for the end product.

Often these two are at enmity with each other. Suitability for one fabricating step, such as machining, may necessitate additional fabricating steps, such as case hardening and final grinding, to achieve "as-fabricated" suitability for the end product. Suitability for the end product may entail extreme difficulty at some of the fabricating steps, as for example, some of the stainless steels which have properties necessary for certain end products are extremely difficult to machine or to stamp.

As-Fabricated. The as-fabricated properties of any product made of wrought metals come from several sources:

(1) Properties inherent in the combination of ingredients in the alloy, and often enhanced by heat-treatments and hot and cold workings at the alloy mills.

(2) Properties imparted by "work" in the fabricating plant, especially if the work be somewhat severe as in forging, stamping, rolling or swaging.

(3) Properties imparted by heat-treatments at the fabricating plant.

(4) Properties imparted by final surfacing operations in the fabricating plant, as for example, the passivating of stainless steel products.

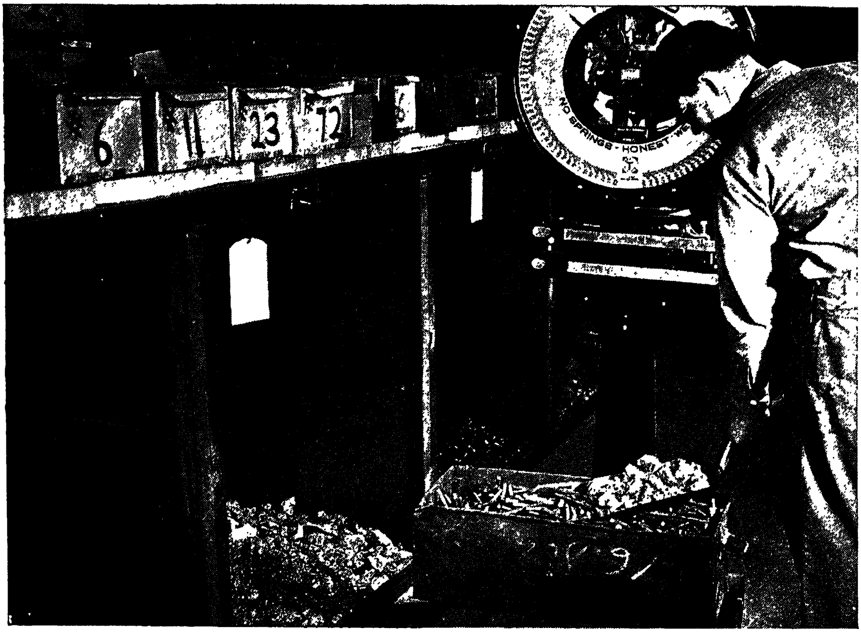
As-Cast. Opposed to all of this, the precision investment casting has the properties inherent in the ingredients of the alloy, plus special heat-treating which can be done while the castings are cooling, plus subsequent heat-treatments and final surfacing operations, although the process prefers to avoid them if practical to do so.

The as-fabricated products and the as-cast ones are to a large degree the results of two opposed schools of production philosophy. These schools can be compared from the viewpoint of the selection of alloys for a given product:

(1) The as-cast product is far more dependent upon properties inherent in the ingredients of the alloys, and is less dependent upon abilities to add as-fabricated properties.

(2) The as-cast product does not need to sacrifice beneficial properties inherent in alloy ingredients because they interfere with fabrication. It does not, for example, need to sacrifice hardness of an alloy because hardness makes for difficult machining and forming.

(3) The as-fabricated product is less dependent upon the ingredients of its alloys.



(Courtesy Haynes Stellite Co., Kokomo, Ind.)

FIGURE 51. Careful compounding of alloy ingredients.

The "Relative" Factors. On the basis of the foregoing simple and absolute comparison, the as-cast and the as-fabricated methods of production need to begin with quite different ingredients in their alloys to arrive at the same properties in their end products. But as every seasoned design engineer knows, industrial matters seldom work out to simplicities or absolutes. There always are modifying factors and even elements of confusion which complicate the simplicities and vitiate the absolutes. Consideration of some of these factors may lead the designer who displaces an as-fabricated process with the as-cast precision investment casting process to make drastic changes in the alloys specified for the products, or narrow changes, or no changes at all.

The Alloys Costs Factor. The cost of a precision investment casting is very largely independent of the alloy cast. This does not mean that a one-pound casting made of platinum will have the same cost as if it were made of 1020 carbon steel, of course. But it does mean that the same casting made of stainless steel may have the same cost as if cast of 1020 steel, and that with the inherent wear resistance of the stainless steel it may avoid the cost of a hardening operation which would be needed by the 1020 steel.

The Service Severity Factor. If the service of the product is severe enough to require extreme strength, hardness, toughness, corrosion resistance, vibration absorption, shock resistance, fatigue resistance, and the like, the as-cast and the as-fabricated products may need to begin with widely different ingredients in their alloys. But if the service is lighter and easier as compared with the bulk, weight, and the strength-imparting contours and accuracies of the product, the differences in those alloys ingredients may be permitted to be wide, narrow or nonexistent. As in all other factors the test of the alloy ingredients is suitability.

The Product Salability Factor. Because precision investment casting is capable of handling so many different alloys with only slight variations of the final product costs, and because the as-cast process does not need the fabricatable properties in its alloys that as-fabricated processes do, the advantage of an alloy which will increase the product salability often may be had by precision investment casting the product. This may mean the use of stainless steels or of aluminums, magnesiums, copper alloys or others which have been so widely advertised to the public that they have definite sales appeals. It may mean adoption of an alloy which has an appealing and distinctive color. It may mean a cobalt or other "known to be hard" alloy which in a machine part will have high appeal to maintenance and production line engineers, or the selection of a high nickel alloy for its known and well publicized corrosion resistance and toughness.

In this the designer can suit his alloy to the sales appeal of his product. He can have an alloy generally believed to be beautiful for a product sold by its beauty, an alloy generally credited with endurance for a product subjected to severe service conditions.

The As-Cast Plus As-Fabricated Factor. In terms of absolutes precision investment casting depends upon as-cast properties for all of its qualities. But there is no reason why, for some products, some of the qualities should not be obtained by secondary operations such as swaging, heat-treating, upsetting or even forging. When the most economical production method turns out to be precision investment casting followed by fabrication operations, the alloy can be selected for its necessary fabricatability.

The Alloy Gradients Factor. Alloys intended for fabrication processes may be of standard grades having wide min-max ranges of ingredients, or if a specific fabricator be a large enough buyer to warrant melting special heats, may be of special min-max ranges of ingredients. But there is no one fabricator so large that he can have all the special min-max ranges in all of the alloys he wants.

Precision investment casting melts its alloys in such small quantities and can operate under such controlled conditions that it can supply these special min-max ranges in any quantities desired. At least one of the world's largest metal products fabrication plants is operating a large precision investment casting department just to get the small lots of special min-max alloy products it needs.

A special min-max may be needed for weldability, as for example, keeping the carbon in steels low enough to promote weldability. As other examples, a special min-max may be needed for specific electrical properties, thermal conduction properties, carbide precipitation avoidance, corrosion resistance, hardenability, avoidance of a final finishing operation, or for fatigue resistance.

There is one modification. Narrow min-max ranges are not always precision investment cast at as low costs as are wide ranges. They should not be specified unless needed.

Also, the designer should look out for the special min-max ranges which he long has had "in the back of his mind" as means of decreasing his fabrication costs. There have been many instances of designers asking the precision investment casters for these when the fabrication operations that needed them were to be minimized or even eliminated by the precision investment castings. Special min-max ranges always should be asked the question "why" before being specified (see Chapter 5).

Stainless Steels an Example of Min-Max Situation. Steels are made stainless by including chromium alone, or chromium and nickel, in their alloy ingredients. They are not considered stainless if they contain less than 12 per cent of chromium, but a lower chromium percentage does impart enough corrosion resistance so that the steels containing it are called "modified stainless" or "stainless irons." To make them resistant against high temperatures, against various corrosive agents, to give them various machining and forging and welding qualities, stainless steels also contain other alloy ingredients in specific percentages. When the total of alloy ingredients other than iron exceeds 50 per cent, the steels are no longer called stainless but are high alloy steels.

One "type" of stainless steel has a set of min-max specifications which makes it suitable for a specific range of conditions. There are about 30 common types, about 20 more which are fairly common, and about 20 which are considered "specials" although their characteristics and purposes are described in some of the sales literature of the stainless alloys mills. This makes a total of 70 types. But the total does not stop there. A fabricator who uses large enough runs to justify special heats can specify that any ingredient of a type be held to the "high side" or the "low side" of the min-max; for example, if the chromium is 12 per cent min, 14 per cent max, that it be held close to the "low" or 12 per cent min end of this range. With these specifications and the low chromium stainless irons or modified stainless, well over 100 types are being made.

Of these 100 there are only about 12 which the fabricator can be sure of getting at any time he wants them, in any shape and thickness of bar or width and gage of sheet he needs, and in any quantity he wants to buy. All the others the buyer may purchase in lots much larger than those needed by any ordinary fabricator; or he may wait a long time for deliveries, or get them when he is lucky, or buy sizes and shapes he does not want and then spend money on fabrication costs to get them machined to the contours of his product, or use substitute grades, or do without the material.

Stainless steels are only one example of this situation. The same problem exists with almost all alloys which are fabricated into end products. Many fabricators have become so accustomed to such troubles that they no longer think about the possibility that there might be some escape.

The ability of precision investment casting to supply those special and generally unobtainable types is of obvious importance. But a statement should be repeated which has been emphasized elsewhere in this chapter. The stainless steel or other alloy type or specific analysis which is ideal for an as-fabricated product might not be at all the one which would be best if that product were to be precision investment cast. The metallurgists of the precision investment casting houses should be consulted about this by the product design engineers.

The "X" Factor. Precision investment casting can obtain properties in some alloys never before obtained in them by any other method whatever. In other alloys it can obtain properties never before achieved by casting but not equal to those obtained by hot- and cold-working or by heat-treating of wrought products. The abilities of precision investment casting to do this vary with alloys and with the casting houses. It will be years before the extents of those abilities are fully known: those abilities are an unknown or "X" factor in the selection of alloys excepting as they have been revealed. But in many cases they can make alloys suitable for purposes for which those alloys previously were not considered. By this means severe problems of design economics may be solved.

There is no "magic" about these results. Precision investment casting simply is subject to closer metallurgical control than any other casting process, especially within the limitations of commercial costs and salabilities of its products.

Precision investment casting works with small bodies of metal, and in small bodies thermal and other physical control is easier. Where there are gas problems in the casting of alloys, as with some aluminum and magnesium alloys, precision investment casting can use controlled atmospheres or operate within vacuums to eliminate them. Precision investment casting can use the "still" casting methods of slow pouring and gravity feeding, or the more "still" methods of raising the metal upward by applying vacuum to the investment, or a slow and still method which includes the use of pneumatic pressure to force the metal into the cavities, or the "shot" methods of forcing the metal in at high speed and under pressure. By controlled use of centrifugal casting, with the centrifugal force applied either parallel or transverse to the main axis of the casting, precision investment casting can resort to phoresis for the control of metallurgical properties. (Phoresis is the forcing of any particles to move through any liquids.) This is possible because at some of their molten temperatures some alloys contain mixtures of liquid and solidified particles.

Precision investment casting can have its invested flasks at any desired temperatures when the alloys are poured. Temperatures can range from those of the melting temperatures of the alloys themselves to the extremely cold ones obtained by packing the invested flasks in Dry Ice for 24 hours before pouring.

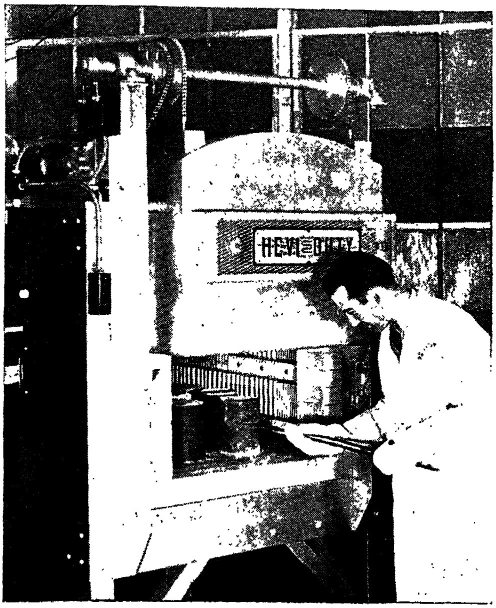


FIGURE 52. The flasks can be at any desired temperatures.

(Courtesy Kerr Mfg. Co., Detroit, Mich.)

As the castings solidify and cool to room temperatures, precision investment casting can control the rate of cooling as desired. The cast metals can be caused to cool slowly through some ranges and more rapidly through others. They can be "jockeyed" back and forth across critical temperature ranges; when crossing their critical ranges, alloys do physical work within their own grain structures and this work can be employed to create desired metallurgical conditions.

One example is a brass consisting generally of 80 per cent copper, 15 per cent zinc and 5 per cent silicon. As ordinarily fabricated by sand casting or die casting this alloy had about 77,000 psi tensile strength and 9 per cent elongation. By precision investment casting it into flasks which were at 1000 degrees F, slow cooling it for 10 minutes after casting, and then quenching the entire flasks in cold water, the tensile strength was raised as high as 93,000 psi and the elongation to 30 per cent. Quenching was for the purpose of immediately disintegrating the investment materials and cooling the castings, the alloy not being known to be quench heat-treatable.

Pouring was tried at various flask temperatures and quenching at various time intervals. It was discovered that wide variants of hardnesses, tensile strengths and other physical properties and of grain structures could be had. The ultimate results of such experiments upon the commercial use of brass cannot be predicted but are likely to be extensive. Precision investment casting provides the necessary means to carry such methods out on a production scale.

In another instance, an extremely thin tool capable of being set up in a lathe for machining steel was wanted. The tool was precision investment cast in ring form of bronze, with the necessary toughness and strength to withstand the operating stresses, and to a Brinell hardness of 575–580 (about 56 Rockwell C).

Phoresis solved one trouble. Experiments were being made with a brass alloy which seemed always to produce dirty metal. Test bars were precision investment cast, the gating being at the ends of the bars. Upon being gripped in the tensile testing machine one end of each bar broke near the grips. Inspection showed that this was always the end which had been furthest from the gate. In the position in which these dispensable patterns had been clustered, this end would be furthest from the centrifugal axis and therefore would receive the greatest centrifugal force. A new cluster of dispensable patterns were lengthened by attaching lumps of wax to the ends opposite the gates, then were invested and cast. The lumps of metal which had been cast where the extra lumps of wax had been, were cut off and proved to contain the dirt which had weakened the metal. The bars then held perfectly in the grips and gave the test results characteristic of clean metal.

Type 350 ST aluminum had 32,000 psi tensile strength as previously processed in one shop. Precision investment cast, the tensile strength went up to 41,000, by elimination of gas porosity.

A lead-bearing bronze was desired to have higher lubricity. Precision investment cast with the casting operation performed at high centrifugal speed, the lead was caused to coat the entire casting. This, of course, had the desired result.

It was desired to find out to what extent centrifugal force as applicable in an ordinary casting machine could be used to obtain gradients of metallurgical qualities in a molten mixture of aluminum and copper. The copper, of course, had much higher specific gravity than the aluminum and could be expected to be affected accordingly by the centrifugal force. No attempt was made to find out whether free copper with its higher melting point, or phases of copper-aluminum alloys with higher melting points than that of aluminum, solidified within the melt and were distributed by phoresis.

An invested flask was prepared by precision investment casting methods and the aluminum-copper mixture cast into it under as high rotational speed as could be applied to the commercial production type of casting machine which was used. The cast bar was 5 inches long by 0.25 inch diameter. The bar was cut apart at each inch along its length and examined for aluminum content.

Beginning at the end nearest the gate and therefore subject to the least centrifugal force, and ending at the end furthest from the gate and subject to the greatest centrifugal force, the percentages of aluminum were found to be:

First inch	4.44% aluminum
Second inch	3.06% aluminum
Third inch	2.10% aluminum
Fourth inch	1.73% aluminum
Fifth inch	1.51% aluminum

No evidence whatever was found of abrupt or "island" segregations of elements. Rather, the transition from one aluminum-copper ratio to another was gradual all along the bar.

A great deal more might have been learned from this experiment. But as is usual with experiments which are carried out under production line conditions this one was discontinued when it had served its purpose of demonstrating that precision investment casting could provide products which had widely different metallurgical conditions at various areas. Such products are needed by industry where one end of a machine part is subjected to different conditions than another.

In some kinds of pneumatic machinery one end of a part may be subjected to heavy shock loads and somewhat high temperatures as it acts as a hammer while the other end is exposed to cold compressed air. It took years of experiment to develop heat-treatments which would produce the different physical qualities needed by the two ends and at the same time which would not produce a transition zone so abrupt that the part would fracture at it. Some internal combustion engine parts, such as valves, need one set of properties at the ends which are subjected to high temperatures in the presence of heavy shock loads and both erosive and corrosive attack by some of the motor fuels, but need entirely different properties at the areas subject only to friction and perhaps to bending stresses, with a third set of properties at the ends which bear against cam shafts or other motion actuators, and all with no abrupt transition zones at which thermal-plus-shock failures will occur. Wide varieties of operations have been tried in the effort to weld three different alloys into a single part which thus would have the necessary characteristics in its three areas, or to find a single alloy which would meet the conditions at all areas. Within some commercial limitations these efforts have succeeded; plenty of L-head automobile engines are running. Within other limitations success has not been obtained. In this and in hundreds of other applications, the ability of precision investment casting to avoid abrupt transition zones while providing different metallurgical properties in different areas of products can solve problems.

The point should be repeated that precision investment casting is not a miracle process which can get literally any desired results with any alloy fed to it. Its results often are so different from those obtained by other processes with a given alloy, that the alloy to be precision investment cast for a given product ought to be selected in accordance with the needs of the product and not by tradition.

To the extent that centrifugal force alone caused dirt to be evacuated from a melt, lead from the alloy ingredients to coat a casting, and progressive gradients of aluminum-copper proportions to exist along a cast bar, any other casting process making use of an investment capable of withstanding the centrifugal force could have accomplished the same results. But the results could not have been those of centrifugal force alone. Successful casting usually depends upon progressive solidification of metal, the metal solidifying first at an area (or at areas) where the heat can be taken away more rapidly than the remaining molten metal will supply it, and solidifying progressively from that area toward the areas which still are molten.

The time at which this progressive solidification or deposition of metal begins depends upon how much above its freezing point the pouring temperature of the alloy is and therefore how many degrees must be removed before solidification can take place at any area, the specific heat of the alloy and therefore how much heat must escape in order to reduce that pouring temperature to the freezing point, the temperature of the investment at the time of casting and therefore the relative rate (T_1–T_2 in the common formulas) at which the molten metal can transfer heat to the investment, and the heat-conducting ability of the investment and therefore the rate at which the heat will be transferred to a final recipient such as the air about the flask. If the flask is cold and is a good conductor, the freezing point will arrive quickly at the first area or areas of solidification. But if the flask is hot and is a poor conductor, the time of first area solidification will be delayed and during that delay desirable events can be caused to take place within the molten metal.

Likewise, the solidification is accompanied by release of latent heat of fusion, and progressive solidification can take place only as more latent heat of fusion is released and finds means of escape. This heat, together with any contributed by the cooling of additional areas of the molten alloy to its solidification point, must escape via the investment or else via exposed sprues and risers. If the investment does not conduct heat rapidly, the progress of the solidification from the solidified areas toward the molten ones will be retarded for a time period during which useful work may be done within, or to, the molten portion of the metal.

If the investment conducts heat more rapidly than the solidified metal in contact with it, the area of that metal in contact with the investment will be cooler than that in contact with the remaining molten metal and shrink strains may be set up in the metal which cools first. This is a matter of degree. Its importance differs with alloys. But if the investment is a relatively poor conductor of heat, the temperature differences between various areas of solidified metal will be less accordingly, and time may be provided during which the heat or other forces can do useful work within the solidified metal. See the example of the 80 per cent copper, 15 per cent zinc, 5 per cent silicon cited on page 103.

More detailed discussions of these points—and there are many other details—belong in scientific treatises on metallurgy. On the evidence given here it may be seen that the kinetics of centrifugal force alone were not responsible for all of the beneficial effects of the precision investment casting process upon these products, but that the often-cited metallurgical factor "time at temperature" (or "times at temperatures") as provided by the insulating values of precision investments also made its contributions.

With many alloys, and dependent upon the physical and other properties desired in the product, there are time-temperature points at which quick cooling to room temperature is necessary. Precision investment is capable of this in that the entire flask may be quenched in water, brine or any other medium. The hot investment usually will fracture under the abrupt change in its ambient temperature, thus exposing the castings to the cooling medium. Investments can be made of specially selected materials which will fracture more completely or even turn to powder when quenched. Other investments are specially prepared so that they will fracture along predetermined cleavage lines and expose some areas of the metal before others. The quench can be controlled.

Steels and Irons

The "X factor," the as yet comparatively unknown ability of precision investment casting to work out problems previously unsolved, also exists in steels and in other ferrous alloys. And this factor can take time and experimental cost to work out. The case history of one critical part is an example.

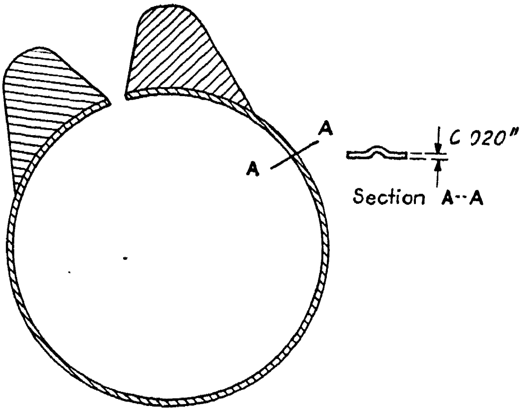


FIGURE 53. Schematic sketch. No important details given. Thin circular casting with heavy lugs.

This part was made of 8630 steel. It was circular in shape, over 5 inches in diameter, about 0.50 inch wide, and had thin sections interspersed with very heavy ones.

The original production method began with strip stock since it was desired to have the directional strength run circumferentially to the finished piece. This stock was annealed, finished to 0.020-inch thickness, rolled with a stiffening corrugation parallel to its length, annealed again to relieve stresses, cut off to length, rolled to circular form, the circle thus being achieved in six operations. The heavy sections were machined to size and shape, brazed on, then remachined to final accuracy. The assembly was heat-treated; then the heavy sections were ground to final accuracy.

Since severe trouble was encountered with braze distortion of such thin stock and with heat-treating to the desired spring temper without having to use the type of high-temperature braze alloy which would cause the most distortion, it was decided to precision investment cast the parts.

The first precision investment casting experiments showed that trouble would be had in casting the 0.020-inch sections in 8630 steel. But since the experiments also showed that this process could hold the carbon content of the alloy at a figure ideal for the spring temper heat-treatment, it was decided to permit these sections to be 0.040 inch thick. The operations then were to: precision investment cast, machine the heavy sections slightly but not anything like the amount and consequent cost previously needed, heat-treat, and to corrective grind.

The precision casting house next discovered that by running heavy sprues so as to retain a bank of heat in the metal within the flasks, and cooling the flasks at a slow and predetermined rate followed by quenching in water when the parts had had sufficient time at temperature for the relief of any residual stresses, the parts could be delivered in the annealed condition and the annealing operation was eliminated. The parts were mildly machined, heat-treated to spring temper, and corrective ground to final size. Costs were very much lower than they had been by original production methods. And since this was desirable from a design standpoint, the precision casting house continued experimenting until it could produce the thin sections to the originally specified 0.020-inch thickness.

The "X factor" was in the flexibility. The 8630 steel as rolled and brazed might have various carbon contents in accordance with the min-max specifications by which this steel is made and commercially sold. Accordingly, as heat-treated for spring temper it would withstand adequate reverse bend tests which were necessary for assembling the part with its mating members, but not as great bend tests as were believed necessary as a factor of safety. Cast metal is expected to be more brittle than wrought metal under bend tests. But the precision investment cast parts as heat-treated for spring temper would take bend tests which exceeded the factor of safety specifications by more than three hundred per cent.

Precision investment casting often results in savings where products are wanted in hardened steels. In one instance a tubular-shaped product was needed to be about 460 Brinell (47 Rockwell C). The original production method was to cast centrifugally a tubular shape, anneal this to about 300 Brinell (about 31 Rockwell C), at which point it was machinable although not easily so, machine it to semifinished contours, heat-treat it to the 460 Brinell, then grind for correction of heat-treating distortion. Precision investment casting delivered this part to the desired hardness, contours and accuracies with no secondary operations whatever.

Common gray cast iron often has been called a difficult alloy to be precision investment cast. But the two questions which need to be asked are: (*1*) *What cast iron?* (*2*) *Why cast iron?*

Cast iron as melted in the old-fashioned foundry is an exceedingly complex alloy. It contains all of the alloying elements and even the dirts which are to be found in "random scrap" and in the pig iron which may come from various sources. Handled by a skilled foundryman it may be caused to be hard or soft, suitable for very heavy sections or relatively thinner ones, adaptable to cored holes and to various external contours. It is melted and its products are sold by the ton. It needs sections thick enough so that "metallurgical averages" will exist within them. This means that any segregations of the elements which are melted for the alloy or of granular structures which may exist within the casting will find no section thin enough so that their existence there will cause that section to be detrimentally harder, more brittle, or otherwise different from the main body of the casting. In short, "common" gray iron castings should have all sections thick enough so that in spite of any segregations all will be reasonably average for the casting.

When sections are thinner than will permit such reasonable averages, gray iron casting abandons the common irons and goes to the "tailored" melts. That is, it melts specially alloyed ingredients and handles them at carefully controlled temperatures which will produce thin sections without detrimental segregations.

Precision investment casting is an exactly similar case. For heavy enough sections it can cast any gray irons that can be melted and cast at all. And because of its exact control of investment temperatures and other conditions, it might cast the common gray irons where sand casting could not. But precision investment casting rarely handles thick sections uncomplicated by thin ones. Products of those contours usually cost less by sand-casting methods. Therefore precision investment casting is more likely to be assigned thin contour products for which it uses much the same "tailored" irons that are employed for thin contour products by the sand-casting foundries. With these it has little trouble.

Slides for high-speed printing presses were precision investment cast of common gray iron. These products had recessed contours which mated with the guide or carrier rails on the presses, but had no thin sections. Cored-in by sand-casting methods the recesses were difficult to machine to the required accuracies, but precision investment cast they needed only slight touching up, and the net cost of the product therefore was less.

Gray iron was preferred for this product because it had been so used for many years and the printing press maker knew exactly how it would behave.

A tailored iron was used for a small part of intricate design. This product had been made of cast iron for 30 years and its user did not propose to experiment with other alloys. In it three moving shafts crossed each other at various angles, threaded holes had to be provided for the assembly members which supported it, oil holes with bell mouths which would invite the nozzle of the oil can had to be cored-in at such angles that they would intercept the bearing bores for the shafts and all oil feed in a downward direction when the part was mounted—all this had to be done in a part no more than 1.5 inches on its longest dimension.

By previous methods the part had been sand cast in solid form with the exception that some of the oil holes were cored-in, then had been machined to final form by complex setups in lathes, drill presses and milling machines. The special tooling was available for work upon the precision investment castings and this fact was wisely permitted to influence the decisions about what dimensions and contours should be "as cast" and what should be machined. All holes in the precision investment castings were cored-in but those for the bearing bores were made slightly undersize to permit broaching or reaming to true smoothness, and those for the support members were also undersize to permit reaming followed by threading by the available special tooling.

Some of the contours had been machined to thicknesses no greater than 0.020 inch. This always had been difficult to do without fracturing cast iron, and had resulted in much spoilage of parts which, at that stage of their production, were high in cost and value. Many of these contours, therefore, as made by the precision investment casting process were assigned to be as-cast. To cast sections of only 0.020-inch thick in gray iron, the casting house used specially selected melting stock plus an additive of high silicon compound. Such compounds can be had in several different proprietary brands, all of which seem to work well. Only about four pounds of additive are required per ton of melt, and in the few pounds to few hundred pounds melts common to precision investment casting, the extra costs of the additive were indiscernible in the overall costs of the castings.

Gray iron can be specified for precision investment casting when its well-known stiffness, vibration dampening, and lubricity qualities contribute to the value of the product. But when it is specified on the traditional basis of "if nothing more costly is needed use gray iron," since the alloys cast have relatively little effect upon the costs of precision investment cast products, many of the casting houses prefer to supply a stainless steel at the same or at even lower net cost.

As between gray iron and 1020 or other low-carbon steel, some casting houses prefer to cast the steel and others the gray iron. The product designer thus has his choice.

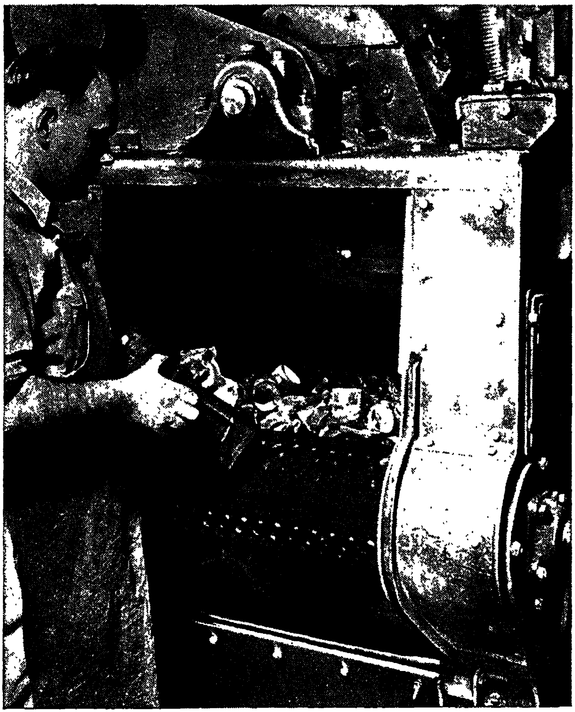
Controlled graphitic irons of the "Meehanite" type can be precision investment cast.

Stainless steels of almost any types can be precision investment cast. Some of them are more free flowing than others and therefore are preferred. Some of those, such as types 416 to 420, which are known to be sluggish in their responses to heat, can require long enough cooling times in the investments so that if there is any possibility of their forming slight slagging compounds with the investment materials they will have plenty of opportunity to do so, and these give trouble to some casting houses. But no two casting houses appear to agree on the types of stainless steels which give trouble. What is easy for one house seems difficult for another, and the reverse. Therefore the product designer should choose his stainless steel in consultation with his casting house, but in exact accordance with the requirements of his product. Where one stainless is as suitable as another, castability should be the deciding factor.

The types of stainless steel which are prone to carbide precipitation with resulting intergranular corrosion can be precision investment cast with complete avoidance of this trouble. The technique as practiced by one casting house is to hold the flasks well above the critical range in which the carbide precipitation occurs. The holding is for sufficient time to assure that the metal has fully solidified. The flasks then are quenched in water; rapid quenching from a temperature above the critical one being the accepted method of preventing carbide precipitation. If desired, the castings can be reheated and requenched just as a factor of safety, but this rarely is considered necessary.

Stainless steels stabilized with various alloying ingredients to prevent carbide precipitation can be precision investment cast. Stabilized stainless steels sometimes are preferred on the basis that the extra cost of the stabilized alloy has only a minor effect upon the net cost per cast product, and that in many instances the stabilization might as well be added for its sales and advertising value to the product.

Some stainless and other steel products can be reduced in value by surface decarburization. This is especially true of tool steels. Decarburization is difficult to avoid completely, since some air usually exists in the pores of the investment. In the great majority of instances the decarburized area is very thin and may be removed by simple grinding operations if not taken off in the grit- or shot-blasting process of getting the investment off from the castings. In



(Courtesy Haynes Stellite Co., Kokomo, Ind.)

FIGURE 54. Shot blasting to remove last vestiges of investment sometimes eliminates decarburized areas.

other instances the decarburized area is recarburized by a secondary heat-treating process. The possibility of surface decarburization often is discussed between buyers of precision investment castings and the representatives of the casting houses but very rarely is a problem in the "as delivered" finished castings.

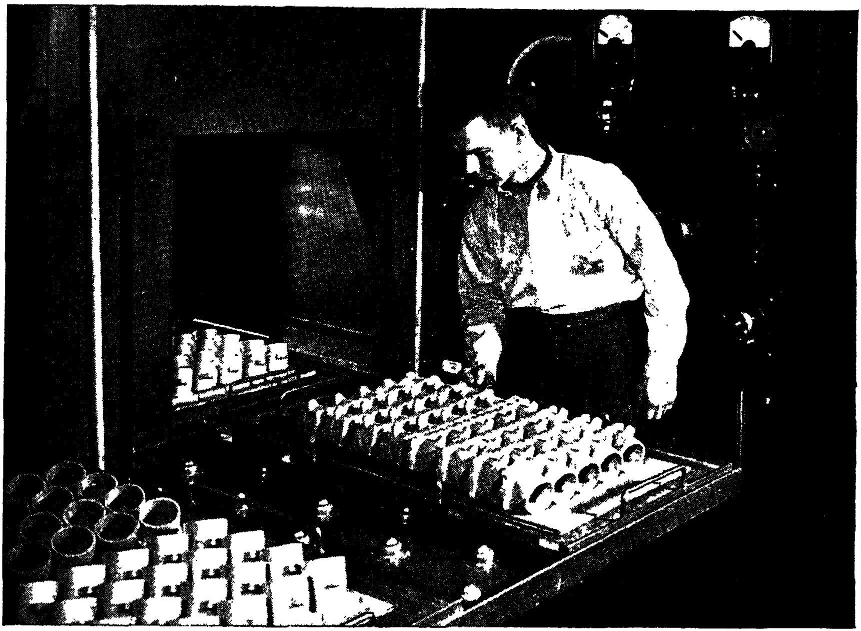
Tool steels are precision investment cast for hundreds of different applications. The use of such castings is increasing very rapidly. There are endless arguments as to whether precision investment cast tool steel tools are better, worse, or about equal to those made by other methods. It must be remembered that tool steel is a highly variable and complex subject; that every tool steel is "as alloyed," and "as cast (if it is cast, some are sintered), "as wrought" if it is rolled or forged or otherwise wrought after casting or sintering (many are not), "as contoured" (the relative thicknesses and shapes of sections make differences as to what may be accomplished by heat-treating), and "as heat-treated" (if it is heat-treated after being contoured to shape). The relative hardnesses, elasticities and other physical properties which may be obtained by heat-treating alone are almost endless.

With all of these possibilities tool steel is the subject of never ceasing research. Precision investment cast tool steels are receiving generous amounts of such research time and money.

Any tool has two values: (1) its ability to help a man or a machine to do more work in less time, (2) its net cost per operation which it performs or aids in performing. A tool cannot have the first of these values unless it can be made at a cost which is commercially practical for the amount of work it is to do. And the second value depends upon the cost to make the tool, as well as upon the tool endurance. On these bases plenty of precision investment cast tool steel tools are fully justifying themselves. See Chapters 3 and 4 for examples.

Tool steels are used in a great many products other than tools. The statement often is made that for these products as well as for outright tools the precision investment cast tool steels are as high as any in resistance to abrasion but are more easily fractured under impacts (are low in impact values). Like any statement that could be made about tool steels, this one is liberally studded with "ifs." *If* the alloy analysis is highly suitable for casting instead of being a specially tailored forging grade; *if* every advantage is taken of the ability of precision investment casting to produce strength-imparting contours; *if* the alloy is such that advantage can be taken of the inherent shock absorbing abilities of cast metallurgical structures; *if* the heat treatment is tailored to a cast rather than to a forged or rolled structure; *if* the casting house has a metallurgist who likes to work with tool steels and has made deep studies of them; in short, *if* the product is planned for precision investment casting rather than being a mere diversion from another process, a high degree of success may be expected.

Precision investment casting does not always need to work with special alloys, contours and heat-treatments in tool steels. Plenty of tool steel items have been assigned to this process with no such changes being made, and these include quite a few in which impact values need to be high. But precision investment casting, like any other production process, should be permitted to make the contributions peculiar to itself whenever they are needed to meet specific conditions.



(Courtesy Haynes Stellite Co., Kokomo, Ind.)

FIGURE 55. Automatic x-ray inspection checks interior soundness of castings.

Other high alloys, sometimes called "tool steels" and sometimes "hard steels," of the high cobalt and chromium and tungsten families are regularly being precision investment cast with excellent results.

Preferred Alloys

Almost every casting house has a list of alloys which it prefers to use for the general run of its production. Alloys are placed on these lists because of their known castabilities, and because the castings houses have become accustomed to them. The lists rarely are completely alike for any two houses. Modifications or changes can be made when products demand them.

Ideal Specification. The ideal specification for any alloy embodies several points:

(1) Suitability for the purpose of the product.

(2) Suitability for machining and other secondary operations if any are to be performed on the casting.

(3) High fluidity to follow the narrow passages in the invested flask.

(4) Sharp liquidity; narrowest mushy range (unless advantage is to be taken of a mushy range to secure specific effects in the castings, see page 107).

(5) Noncritical melting points.

(6) Non-segregating, non-separating (unless segregation is desired, see page 105).

(7) Low shrinkage characteristics.

(8) Not chemically reactive with commonly used investment materials.

(9) Cost of metal is relatively unimportant.

One product designer gave a casting house its choice of either 1020 or stainless steel in a product in which no free ferrite segregations were wanted. Free ferrite, in the instance of this one product, was found in both of these. A change to 8080 steel corrected the trouble.

In another instance a casting house was asked to produce a product of intricate contours in low-carbon steel. The steel proved to be sufficiently reactive with the investment material in use in that house so that a different material would have to be substituted. This second investment material was higher enough in cost to affect the prices of the castings, and added greatly to the difficulties of producing the invested flasks. A change from the low-carbon steel to a free-flowing, low-reactive stainless steel reduced the production costs and yielded an end product which was highly superior for its intended functions.

Light Alloys vs Porosity. All of the light alloys such as aluminum and magnesium are readily handled by precision investment casting methods. In fact, these alloys have worth-while advantages for some products in that the sizes of castings which this process can make are largely dependent upon the kinetic forces imposed by the molten metals upon the investments as compared to the structural strengths of the investments. These forces are proportional to such factors as the total weight of metal cast into a given cavity, the total surface area of the casting and therefore the area over which the pressures and erosive forces will be imposed, and the temperature of the molten metal and therefore the amounts of temperature weakening effects which will be felt by the investment walls and other areas. All of these factors are highly favorable to lightweight alloys as compared to the heavier ones which also have higher melting and pouring temperatures. The largest single castings which so far have been known to be precision investment cast, each casting being 25 pounds in weight and 18 inches on its longest dimension, were aluminum.

Lightweight alloys are variously subject to porosity. The porosity is seriously weakening to physical strength, can have undesired electrical and other energy transmission and control effects, can seriously reduce the abilities of the alloys to be plated or welded or polished, and can greatly reduce their abilities to retain liquids and gases.

Nearly all light metal alloy materials begin as castings. The point is not being argued here as to whether extrusions which make up a small percentage of original production from the melted alloys do or do not "have the metallurgical natures of castings." Wrought operations such as rolling and drawing generally do not heal any major porosity originally formed in the ingot castings, although by careful control of casting methods and careful selection of the ingots and the portions of ingots to be wrought very excellent wrought products are produced for wide varieties of uses.

Extensive research is being conducted regarding this porosity subject, and for more complete information the reader is referred to the literature. Certain facts revealed by researchers point clearly to reasons why precision investment casting is able to produce light metal products which are comparatively free of porosity problems and therefore are superior to similar products made by other processes. Among these indications are:

(1) Porosity problems are largely a matter of the alloys selected. Precision investment casting can select its alloys as desired.

(2) The sizes and shapes of the porosities have important bearing upon their effects upon the castings, tiny and round "pinholes" being generally less damaging than larger and "rectangular" shapes. The sizes and shapes

depend largely upon the pressures applied while casting. Precision investment casting can apply the desired pressures with very close control and over wide selectivities of pressure ranges.

(3) The amounts of porosity are largely determined by the amounts of hydrogen available to the molten metal at the time of pouring. This hydrogen can be present in moisture in the sand if the metal is poured into sand molds, or in the air. Precision investment castings can be poured into investments which are too hot for either moisture or free hydrogen to exist in them, and under vacuum conditions which nearly preclude the picking up of hydrogen from the air about the investments.

(4) Gas which is entrapped in the metal, as it might be in the pigs or the scrap which are melted to make precision investment castings, has a tendency to escape if permitted to do so. Slow cooling of the casting can sometimes result in retarded solidification of the metal with increased duration of the opportunity for the imprisoned gas to escape. Precision investment casting normally provides slow cooling but can provide nearly any desired cooling rate.

(5) The escape of the imprisoned gas can be encouraged by vacuum casting methods in precision investment casting if necessary. In these the entire flask can be under vacuum and the turbulence of the metal as it flows into the flask can bring successive areas of the molten metal to the surface where the vacuum will have the greatest effect upon the gas.

(6) The tendencies of the porosities to form are largely dependent upon the thicknesses of the cast sections, the gases nearest the surfaces being most likely to escape and those in the interiors most likely to be imprisoned, the greatest and most weakening porosities therefore commonly being found in the middle of thick sections. Precision investment castings rarely have thick enough sections to imprison extensive amounts of gas, therefore these castings are likely to be of uniform soundness throughout.

With the factors which are commonly understood to cause porosity and to influence the effects of porosity all subject to control in precision investment casting, this process often produces light metal products having 50 per cent greater tensile and other strengths than similar products made by other processes, and sometimes produces 100 per cent greater strengths.

Progressive Deposition in Light Alloys. Lightweight alloys can have such high coefficients of thermal conduction that it is difficult to cool one area of a poured casting more rapidly than another. Therefore progressive deposition of metal can be difficult to achieve, and all areas of castings can have tendencies to solidify simultaneously, with the result that shrink porosities are produced in some or in all areas.

Shrink porosities can be even less controllable and more weakening than gas porosities. A common way of controlling them is to feed the castings with large volume risers so that the metal keeps on feeding and filling in the voids until freezing is complete. This method is as open to precision investment casting as to sand casting. For example, one precision investment casting operation was gravity poured; 7.5 pounds of aluminum were poured for every 2.5 pounds of finished castings. But the method does not always work. Light metal castings, especially those having heavier sections than are common to precision investment castings, often have irregularly "rectangular"-shaped voids which give evidence of being at locations where some metal solidified and formed crystals while other metal about them still was liquid, and this can happen in areas where the gravity fed supplies of liquid metal do not readily penetrate to fill the voids.

Centrifugal force or else direct pressure can help to close these voids by applying more pressure than is obtainable from the gravity feeding of the metal. Pressure-casting methods are common to precision investment casting; and because the castings ordinarily are small, the pressures are exerted over relatively small areas and are controllable.

Chill areas can cause or promote progressive solidification of light metal castings. Precision investment casting rarely uses outright chill plates, although there is no valid reason why it should not do so, especially for such low-melting temperature alloys as the common light metals. But precision investment casting can use such methods as freezing the investments in Dry Ice. In one example the investments were packed overnight in Dry Ice and then poured at the beginning of the day shift. Casting was by gravity, and whereas 7.5 pounds of aluminum had to be poured into hot investments to yield 2.5 pounds of castings, only 3.5 pounds were needed with the chilled molds, the extra pound representing the sprue and runner metal. The castings were free of porosity to an excellent degree. This chilled mold method appears to have been independently discovered in several precision investment casting houses.

With the possible exception of the chilled mold, precision investment casting does not seem to have contributed any new techniques to the control of gas and shrink porosities in light metals. The process owes its outstanding successes with these alloys, first to the fact that it handles them in such small unit volumes and weights that control is comparatively easy, and second to the advantages of its own high controllability and adaptability as a casting process.

Aside from the importance of making these lightweight and strong alloys more useful to industry, precision investment casting here can enable industry to operate at all. There is a known and serious shortage of the ferrous alloys. Industry can keep on producing and fabricating them in just about their present volumes for some time to come, but those volumes are not enough. The known resources for light metals, especially magnesium, are inexhaustible in terms of industrial demand. The problems of substituting them for steels are largely those of metallurgical control. Within its field, precision investment casting provides a great deal of that control.

Other Nonferrous Metals. Copper alloys such as brass and bronze are among the easiest to cast. But not all casting houses get equal results with them.

For parts of no more than ordinary intricacies common plaster of Paris can be used as an investment material, although some of the proprietary investments are better. In fact, most of these alloys handle so easily that the average brand new casting house begins with bronze, brass, or silver, and then progresses to the more difficult alloys.

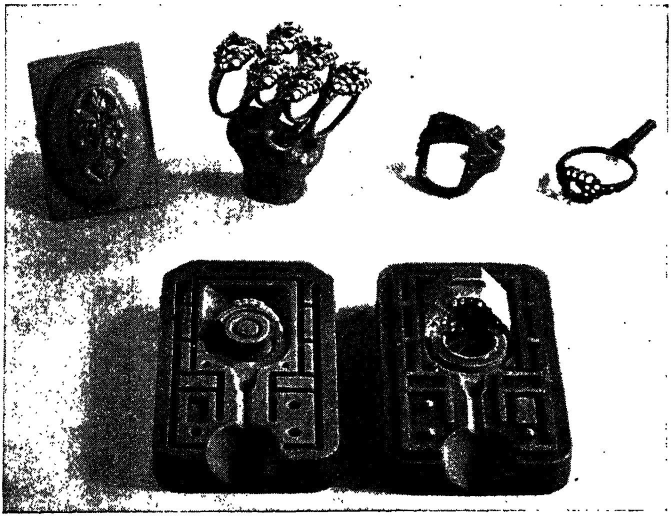
When really intricate work is needed, very high strength or other properties, these alloys still are among the easiest to handle, but require specially developed techniques. In the hands of metallurgists who have these techniques, a great many of the cast bronze, brass, and beryllium-copper alloys as-cast can be caused to equal or exceed any properties obtainable in their wrought forms, and certainly can be made to equal any American Society for Testing Materials (ASTM) specifications for the wrought forms.

The smallest holes which are castable at all by this process are produced in copper alloys. Some of these holes are less than 0.020 inch in diameter.

The closest tolerances and highest fidelities to contour details also are cast in these alloys. There are several reasons for these advantages. First of all, investment materials can be used which are highly liquid when being applied but harden completely and accurately, and therefore intricate contours can be wetted out by them and small holes filled. Secondly, the melting points of the alloys are not high enough to cause trouble for this process. Thirdly, the thermal conductivity of the alloy is almost ideal. The thermal conductivities of these alloys ordinarily are not high enough so that the molten metal will prevent progressive deposition, nor low enough so that the cooling will be sluggish. A fourth reason for the advantages of these alloys is that they are heat-treatable in ways which this process handles easily. They can be annealed by careful control of the cooling rate of the flask after pouring.

The castings also can be removed from the flask and then heat-treated. Beryllium-copper castings have been heat-treated for three hours at 600 degrees F, thus securing tensile strengths up to 110,000 psi. The same alloy castings were annealed at 1475 degrees F, quenched in water, then heat-treated for three hours at 600 degrees F, and had tensile strengths up to 186,000 psi. These alloys may be made as hard as 400 Brinell.

Nonferrous Metals for Design Development. Where the design economies of steel precision investment cast products are not fully known, the high castabilities of copper alloys often are used for trial runs of parts. These runs may be in lots of several thousand for testing in the field. The designs may be perfected by making changes in new runs. Many such designs have been changed to steel only after a year or more of testing. And the copper alloys have been known to make such good records that they held the business.



(Courtesy Kerr Mfg. Co., Detroit, Mich.)

FIGURE 56. Most of precious metal casting is for jewelry.

Precious Metals. Any of the "noble" metals which can be cast at all can be handled by precision investment casting. In fact some members of the platinum family are said to be castable by no other process. Silver is as castable as the most castable of the brasses by this process.

There is very little casting of these alloys for industrial purposes, most of them being cast as jewelry. But the use of noble metals in bearings, for electrical contact and other parts, for thermocouple and other products exposed to high temperatures, for products exposed to chemicals which are strongly corrosive to other alloys, and for precision instruments parts, may be expected to increase "if and when" the prices of these alloys as raw materials go down to reasonable levels or the government ceases to control some of them as instruments of international politics.

The casting of these products for jewelry purposes is, in general, crude in terms of accuracies achieved and of metallurgical control, nothing more being attempted than the securing of strengths and of contours adequate for beautiful ornaments. Some of the jewelry casting houses do respect the fact that with higher accuracies they can make important savings on the amounts of high cost metals cast for a given sales volume, and with close metallurgical control they can make much better products, and these houses have developed careful methods accordingly. But the product designer who specifies a precious or noble metal and turns to a casting house habituated to the casting of that alloy must select that house with great care.

High Melting Point Nonferrous Alloys. Various alloys of cobalt, nickel, chromium, molybdenum and other metals, which contain either no iron at all or else very little iron, are however so high in their melting and pouring temperatures as to be classed with the ferrous alloys as casting problems. Often these are actually easier to cast than the ferrous metals. They have extremely narrow plastic temperature ranges as compared to those of ferrous alloys; also they obtain and retain high strength at elevated temperatures, and therefore have fewer plastic distortion problems while being cast. Since most of them are nearly unmachinable, they compete against forgings rather than against machined parts. Their principal use is for high temperature service.

"Plastic Range" Rule of Thumb. Although the term "plastic temperature range" is subject to various interpretations, the forging temperature range is a rough "rule of thumb" index adequate for nearly all casting purposes.

Chapter 8

Dimensions, Accuracies and Contours

As stunts, casting houses have captured cockroaches, invested them without duplicating them in wax, led wax sprues to them, baked the invested flasks to remove the wax and as much of the insect bodies as would burn out, poured in bronze by centrifugal casting methods, and come out with bronze cockroaches mounted on sprues. Flies and spiders have been similarly cast. All the fine details of the wings of the fly, the legs of the cockroach, and even some of the fine hairs of the spider have been brought out.

From such demonstrations many factors of importance to precision investment casting may be observed:

(1) The alloy was highly castable. This stunt could not have been performed with alloys which were not free-flowing or which were critical in their melting points, pouring ranges or other metallurgical factors.

(2) The alloy could be poured into an investment which had practically no chemical reaction with it, and which could be removed by dissolving it in water and without the need for any mechanical force.

(3) The extremely fine parts such as hairs and legs had large bodies of metal in the insect body sections and the sprues from which to draw. If these fine parts had been wanted as separate products, the proportions of excess metal to actual castings in the investments would have been high.

Almost anything in the matter of dimensions, accuracies and contours which can be produced by precision investment casting is highly dependent upon the alloys selected for casting. This is one of the principal reasons why, so long as the alloy results in a product economical for its function, the casting house should be permitted to select the alloy to be cast.

Preferred Sizes vs Casting Houses. Each casting house has its preferred list of weights, dimensions and accuracies to which it prefers to work. With some houses these ranges are wide, with others narrow. All that can be done here is to tell what is general for the field. The individual casting houses should be consulted.

Weights. The lightest weight precision investment castings in regular commercial production weigh only a small fraction of a gram apiece. The heaviest ones in nonferrous metal are 25 pounds (aluminum), and in ferrous metal 35 pounds in stainless steel. There is no reason inherent in the process why still heavier ones should not be cast.

Preferred weights for the field as a whole are in the range of 1 gram to 8 ounces. Preferred weights for some houses, especially those which specialize in steel and in the extremely hard and high-temperature alloys, are 1 ounce to 1 pound.

Limit weight for the most practical field is 4 pounds. But some houses go to 10 and even 20 pounds as their practical limit.

Sizes. Sizes of precision investment castings can exist in terms of overall dimensions and of thicknesses of solid sections. To some extent the two are contradictory in their effects upon the process. The practicalities of both factors vary greatly with the alloys to be cast. These problems often can be solved by letting the casting house choose the alloy, so long as it selects one economically suited to the function of the product.

Sizes also can be in terms of thinner sections continuous with thicker ones. Thinnest edges on pieces of continuously increasing thicknesses as measured from their edges (knife blades, for example) are 0.005 inch as cast in a hard metal which is not of the highest castability. In extremely castable metals such edges have been produced as thin as 0.0015 inch.

Thinnest wire forms are 0.002 inch and as long as 2 inches. No attempt seems to have been made to find their greatest castable lengths since they have few commercial uses.

Thinnest continuous sections are 0.005 inch thick on pieces 0.25 inch long by 0.125 inch wide. Thinnest sections continuous with thick sections are 0.002 inch thick.

Thickest solid and continuous sections are 5 inches thick. But there is no reason inherent in the process why thicker ones should not be cast.

Thinnest *preferred* sections are 0.020 inch thick in the most easily castable alloys, and 0.040 inch in the less castable ones. The 0.020 inch preferred minimum has been achieved in alloys which are extremely intricate in their casting procedures, but only after long and costly experiment with the desired product.

Thickest *preferred* solid sections are 0.375 inch thick, and for many casting houses are 0.250 inch thick. Thick and solid sections increase every problem of casting. Dispensable patterns become liable to expansion and contraction troubles which strain or break investments. Investment walls must be thicker and stronger, with increased likelihoods of cracking or spalling.

The problems of thick sections are multiplied when the castings are to be heat-treated either in the flasks or after being removed from the flasks. Responsiveness to heat-treatment varies with the changes which are caused to take place within the metallurgical structure of the alloy and with the thermal conduction rate of the alloy *vs* the distance which the heat must travel to get into or out of the center of the section. When an alloy is sluggish in its response to heat-treatments these problems can be especially severe, but they can be quite severe with alloys which are not sluggish. The same problems exist with thick sections to be produced by any process. Precision investment casting excels in its abilities to obtain bulk and strength without the use of heavy sections and so is able in large measure to avoid these heat-treating penalties.

Other troubles caused by thick sections include increased cost for investment, increased setting time with consequent greater cost for applying the investment, increased sensitivity of investment, increased proportion of spoiled and rejected castings, increased inspection costs, increased costs of metals melting and casting, and increased solidifying and cooling time with the result that if the alloy has any chemical reaction with the investment material, more time is provided during which it can take place.

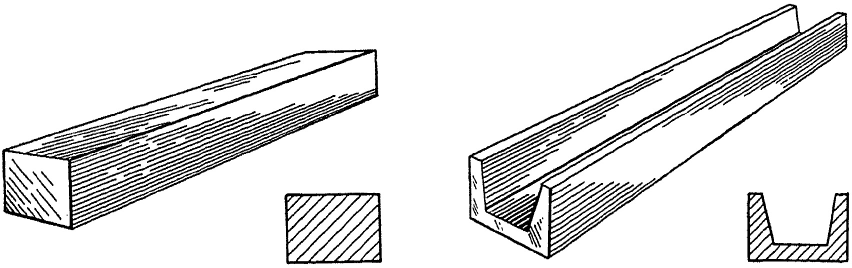
In spite of these troubles thicker sections can be cast where they are economically desirable. They are not preferred.

Shortest dimensions are those of thickness, as specified above. Longest *preferred* dimension is from 1.5 to 2 inches. Dimensions as long as 4 inches are within the easily practical range. The range of practicality limits extends only to 5 or 7 inches for many casting houses. Dimensions over 20 inches have been cast commercially and in alloys which are not the highest in castability. There is no reason inherent in the process why still longer dimensions should not be cast if economically justified.

Extra-long dimensions, especially if accompanied by very wide ones, create much the same investment problems as those detailed for thick sections. But if not accompanied by thickness of sections, long and wide dimensions do not have the thick section problems of dispensable pattern troubles, metals melting and casting, and heat-treating.

In one quite typical example a part which would act as a shaft key had to be of extremely hard alloy to meet operating conditions. Cast as a solid section 0.50 inch thick, it was very difficult to bring to the desired accuracy.

Machining this product to the desired accuracy was difficult because of the hardness of the alloy. But redesigned so that a truncated wedge-shaped channel was cast throughout its length, the product became easily castable to tolerances which required only a little surface grinding to come within the desired limits. The channeling also eliminated 55 per cent of the weight of the part, and this was desirable not only to reduce the weight of the assembly in which the product was used, but also to minimize the problems of dynamic balancing.



Solid section difficult to cast.

Reduced weight part functionally superior and easy to cast.

FIGURE 57.

Thin-Walled Products. Precision investment castings are made hollow or with thin walls to reduce thick sections to thin ones, to reduce weights, to provide passages through which liquids or gases can flow, to provide convenient means of products assembly, and to reduce heat-treating problems. When metals are high in cost or are restricted in supply, precision investment castings may be made hollow to conserve them.

Preferred minimum wall thickness is 0.040 inch for all alloys; but for highly castable alloys 0.020 inch walls may be used.

Preferred bores or interiors are generally round although not necessarily truly circular, and are at least 0.25 inch in diameter, there being no maximum diameter. If these bores have straight sides they should not be cast with truly angular corners unless absolutely necessary to do so. Such corners are hot spots and can cause severe shrinkage troubles. Fillets at these corners can reduce these troubles. If truly angular interior corners are needed it generally is less costly to cast them with fillets and then broach or otherwise machine them out. *Preferred* bores go clear through rather than being chambers.

Holes and Chambers. Holes and chambers are cast or "cored" into precision investment castings for purposes functional to the product, to reduce casting problems, or for both reasons.

When the hole or chamber takes any part in the relief of a casting problem, the cooling metal will shrink toward it, away from it, or toward some parts of its contours and away from others. What happens in these respects depends upon the sizes, weights, and thicknesses of contiguous and of neighboring sections of the casting; the positions of sprues and risers in relation to the hole; and the directions and rates of the progressive depositions of the molten metal. The investment material in the core must be brittle or fragile enough so that the cooling metal can fracture or crush it; otherwise the investment material will hold against the shrinkage forces of the metal and will set up shrink strains within the metal. (Non-crushable cores are discussed on page 129.)

Obviously, under these circumstances the hole may not have the same contours as the original core. A round cored hole may be cast out of round; a square core may produce a hole with somewhat rounded sides; any straight contour on the core may come out slightly concave or convex in the casting. In a new design these effects may not be completely predictable until experimental runs of castings have shown what they are.

When the contours of the hole or chamber conform regularly to those of the casting and the casting itself has no sections of such nature as to set up irregular shrinkage strains, the hole may be the same shape as the core but its dimensions may be changed by the shrinkage.

Much depends upon the size and the location of the hole in relation to the overall dimensions of the casting. A relatively small hole with large masses of metal all about it neither will change much in its contours nor contribute much to the solutions of shrinkage problems. The same hole with heavy metal on one side and light sections on the other may change in contours, and rather than relieve shrinkage problems, may create them. For example, a small hole cored-in at the bore of a gear would hold its size and dimensions, while the same-sized hole which nearly interrupted the periphery might hold neither.

Much also depends upon the metals cast. In highly castable alloys the shrinkage problems are much less than in those intricate to cast. A hole, recess or chamber may be needed to relieve shrinkage problems in an alloy of low castability, whereas if the casting house were allowed to use an alloy of higher castability but equally suitable for the function of the product, the hole would not be needed.

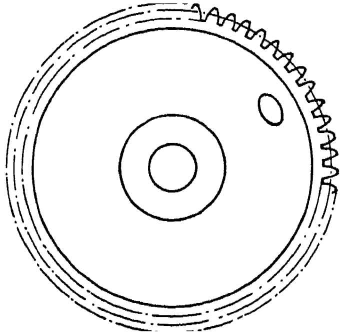


FIGURE 58. Hole cored-in with a crushable core (*center*) might remain round. Similarly cored one (*side*) probably would be shrink deformed.

From these problems the casting houses have evolved several preferred practices.

Holes for Shrink Relief Only. When the sole purpose of the hole, chamber or recess is the relief or prevention of shrink strains in critical areas of the casting, it is *preferred* practice to specify that the hole contours may come "at random" or "as cast" so long as they are not detrimental to the functioning or the sale of the product.

Drillable Holes. If holes may readily be drilled it is *preferred* practice that they be drilled rather than cored in. The drilling usually is less costly. If desired, the casting design may include drill guide recesses which also can act as countersinks after the drilling is completed. The casting design also can include bosses or guide holes where holes are to be drilled at odd angles (see Chapter 5, page 65).

Accurate Holes in Shrink Strain Areas. When a round hole is to be drilled, or a hole of other contours is to be broached or otherwise produced in an area in which shrink strains are likely to exist, it is *preferred* practice that a smaller hole be cored-in and then be machined to size.

A drill entering shrink-strained solid metal is likely to turn and follow the porosity or other conditions produced by the shrink. The result may be a crooked or an off-path hole, or even a broken drill.

But if a smaller hole is cored-in, the shrink strains will be relieved even if only slightly, the metal about the hole will be solid, and the drill need only act as a heavy reamer. Likewise a broach or other tool will find solid metal and its task made easier.

Gang Drills. When a multiple drill head may be used to drill several holes simultaneously, it is *preferred* practice to core-in one hole to act as a guide. This hole should be smaller in diameter than the drill and can be highly accurate in its location. Such practice speeds the drilling operation and often eliminates the need for expensive jigs, fixtures and other tooling of the drill press.

Non-Machinable Holes. Sometimes because of location, size in relation to wall thickness, or hardness or other low machinability of the alloy, holes may be difficult to machine in any way. Each such product must be handled in its own way. There are too many possible variables to permit the development of general or preferred practices.

Experiment and experience often will show the casting house how to design crushable cores which are of such contours that when the shrinkage has ceased the resultant hole or chamber will be of the desired location, contours and dimensions. Non-crushable cores may be used, although their effects upon shrink strains must be studied.

In one instance a part which must endure severe corrosive and abrasive conditions while withstanding high speed dynamic loads and holding pressures up to 20,000 psi, was wanted. The exterior contours were such that precision investment casting them was indicated. The bore had to be highly accurate. The alloy selected for such conditions was too hard to be machined at all or even to be ground readily. Therefore precision investment casting had to hold the accuracy of the bore.

The wax which was to be used as dispensable pattern material was experimentally injected into molds under several different pressures and temperatures, and was found to hold high accuracies if injected at 20,000 psi pressure and a plastic temperature of 126 to 128 degrees F, rather than at a liquid temperature. Cores having enough structural strength to restrain the shrinkage of the cooling metal were centerless ground to the correct sizes and contours within ±0.00025 inch. The invested flasks were kept as cold as was possible without actually freezing the metal before it could fill out the cavities. The metal was poured at the lowest possible temperature, a temperature which actually was close to the bottom of its mushy range.

The behavior of the dispensable pattern is interesting. The mold for making the pattern was 2.983 inches in inside diameter. The pattern material shrank to 2.975 inches in outside diameter. The finished castings had inside diameters of 2.951 to 2.952 inches, thus proving that even with an alloy of comparatively low castability it is possible by careful but somewhat costly methods to hold within a tolerance of 0.0005 inch on a 3-inch bore.

The ability of the non-crushable core to hold against the shrink forces of the metal is not completely known but can be roughly indicated. Total or net shrink of dispensable pattern and of metal usually is about 1.5 per cent of the diameter of the mold interior. It is not known to what total extent the pattern may expand within the investment and thus increase or otherwise alter the dimensions of the investment cavity within which the metal may shrink, and therefore the proportion of the total shrink which should be credited to the pattern material as compared to that of the alloy. But this 1.5 per cent normal shrink would have amounted to about 0.0447 inch on the 2.983-inch mold interior dimension. Actual total shrink was 0.0032 inch, or some 7 per cent of normal.

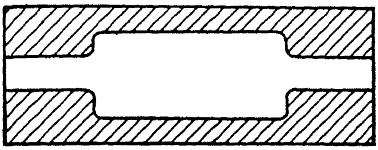
Careful x-ray inspections were made to be certain that the restraining of the shrink had not resulted in internal hot tears. None were found. In their absence it was determined that no residual stresses which would weaken this extremely high-strength alloy had been set up. And in service the products proved fully adequate. The costs of shrink-restraint justified themselves.

This experience demonstrates that shrink can be restrained although extremely careful casting methods must be followed unless the design strength of the product and its alloy are highly superior to the requirements of its function, and that production methods which do not require the restraint of shrink are to be preferred when they can be used.

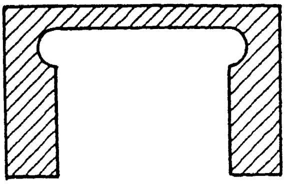
Undercuts and Re-entrant Orifices. Any chamber or recess which has an orifice smaller than its inside diameter, and any undercut (chamber which has its entrance at the periphery but not at the entrance of a hole) can be cast. But the chamber with a small orifice involves a re-entrant angle with a consequent hot spot and other shrink troubles. The undercut involves similiar troubles, and if it also has re-entrant angles, it can be one of the worst of casting problems.

Such designs never are *preferred* by the casting houses. But these designs often are highly valuable because they provide reliefs and other design features. Therefore a great many of them are being cast. The casting houses should be permitted to refine the designs into the most castable ones which are economical for the function of the product and to work with the most castable alloys.

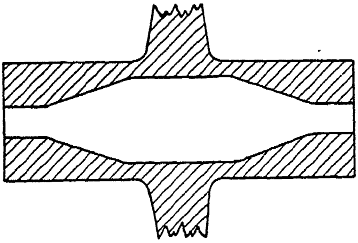
The design changes commonly involve curvatures, interior fillets, ribs, other means for equalizing heat distribution while the newly solidified cast metal is cooling and shrinking through its plastic ranges to its fully solid one, and from that to room temperature. The absence of these features in the original design usually is not caused by functional reasons but by the fact that with the originally planned production method they could not be produced. There rarely is any reason why the changes should not be made in redesigning for precision investment casting.



Internal relief under cut. All internal corners should be rounded.



Locking channel under cut. Often in guide members.



Opposed taper under cut. The split tapered members are inserted and the assembly is placed on the shaft. Tightening the taper nuts fastens the unit to worn shafts.

FIGURE 59.

Minimum Diameters of Holes. Minimum *preferred* diameter of cored-in holes for all metals is 0.040 inch, and for alloys of low castabilities this also is the practical minimum. In alloys of higher castabilities the practical minimum is 0.020 inch, although holes as small as 0.010 inch have been cored on a commercial basis.

Radii. The minimum radius possible to produce on any contour is a function of surface finish obtainable and therefore is directly related to the alloy cast. If the alloy can be used with an investment which can be removed by dissolving it or otherwise without the use of grit blasting or any other mechanical force, and if the surface of the casting does not oxidize while cooling and has no chemical reaction with the investment material, the minimum radius obtainable is fine indeed. But if the opposite conditions exist, the amount of damage done the surface of the casting can limit the fineness of the radii. *Preferred* minimum radii are on the order of 0.008 inch. Any finer ones desired should be discussed with the casting houses.

There is no trouble with sequences of radii such as are wanted in cam shapes. In fact precision investment casting, because of the problems of progressive deposition of metals, often finds these less troublesome than truly circular shapes.

Accuracy and Precision

The product design created for precision investment casting may have certain necessary limits or tolerances. The selection of the ones which actually contribute anything to the value of the product was discussed in Chapter 5. Once this question has been settled, the process is required to produce its first runs of parts with accuracy and to continue to produce subsequent lots with precision. Or, when the limits are difficult to hold, the process must make reasonable percentages of each production run with the necessary precision and scrap the remainder.

Original accuracy is largely a matter of preparational cost. The castings cannot be any more accurate than the dispensable patterns, and the patterns cannot be more accurate than the molds or other tools with which they are made.

Intricacies of product contours make important differences, of course. Some contours are much simpler to produce accurately in the molds and dies than are others. But in general, the higher the accuracy, the higher the preparational cost. It is *preferred* practice to devote as much of the preparational cost to the dimensions which really need precision and as little to those which do not, as is practical.

The costs of obtaining accuracy on the master patterns from which the molds for forming the dispensable patterns often are made, or on dies for this purpose, varies with the dimensions and contours of various areas. Every toolmaker knows that dependent upon his toolroom equipment there are dimensions so small as to be difficult to machine or grind to high accuracies, dimensions so large that accuracy is difficult, and surfaces of difficult contours. There also are median dimensions and contours on which accuracy is easier and less costly to obtain.

It is *preferred* practice to specify high preparational accuracies only on dimensions and contours on which they are easy to achieve. High accuracies on other areas may be had, but the tool costs are raised accordingly.

Once the desired preparational accuracy has been achieved, precision production becomes a matter of control. Control economics are the same for all industrial processes. The more exact the control the higher its cost. Too little control costs more for spoiled work than too much control does for operating difficulties.

It is *preferred* practice for each casting house to seek a median degree of control typical of the alloys and products it customarily makes, and to tighten that control only when necessity warrants added costs.

Control for precision is largely a matter of shrinkages and expansions. Whatever works to make the casting dimensions shrink is shrinkage, and whatever makes those dimensions become larger is expansion. Confusing terms such as "reverse shrink" should be avoided.

Net Shrink. Dispensable patterns shrink as they cool but expand while being melted out. Investments expand (usually) as they set and also as they are heated up. Molten alloys shrink as they cool. The total effect upon the dimensions of the casting is "net shrink."

The net shrink never is completely the same for the castings in any two flasks nor even for any two castings poured simultaneously into the same flask. Dozens of factors of pressures, temperatures, holding times and chemical mixtures must vary at least slightly; therefore the castings must vary at least slightly. And each variation becomes a modification of precision (precision being the repeated duplication of accurate dimensions, contours and properties).

If a piece of metal 1 inch long contracts about 0.001 inch when its temperature is reduced a given number of degrees F, under the same conditions a piece of the same metal but 2 inches long will contract about 0.002 inch. Therefore the net shrink, if unrestrained, always will be in terms of thousandths of an inch per dimensional inch of the casting. That is why it is *preferred* practice to specify basic tolerances in terms of thousandths of an inch per inch.

Basic tolerances depend upon variabilities. They are wide (plus or minus 0.008 inch per inch, for example) if variabilities are wide, and are narrow (plus or minus 0.001 inch per inch) if variabilities are under close control. It is *preferred* practice, therefore, for each casting house to find a class of minimum basic tolerances to which it works for most of its production but which it can make narrower by closer control if the added cost is economically justified by its effect upon the functional value of the product.

There are bottom practical limits to basic tolerances. For example, if the basic tolerance of a casting house is plus or minus 0.004 inch per inch then the actual tolerance will be plus or minus 0.002 inch on an 0.50-inch dimension and plus or minus 0.001 inch on an 0.250-inch dimension, but the tolerance will not go on down to plus or minus 0.0005 inch on an 0.125-inch dimension. On the contrary, the minimum tolerance for that house is likely to be plus or minus 0.001 inch. Therefore it is *preferred* practice to specify minimum dimensions beyond which actual basic tolerances do not become narrower. This minimum dimension usually is 0.250 inch but this selection is not uniform for all casting houses.

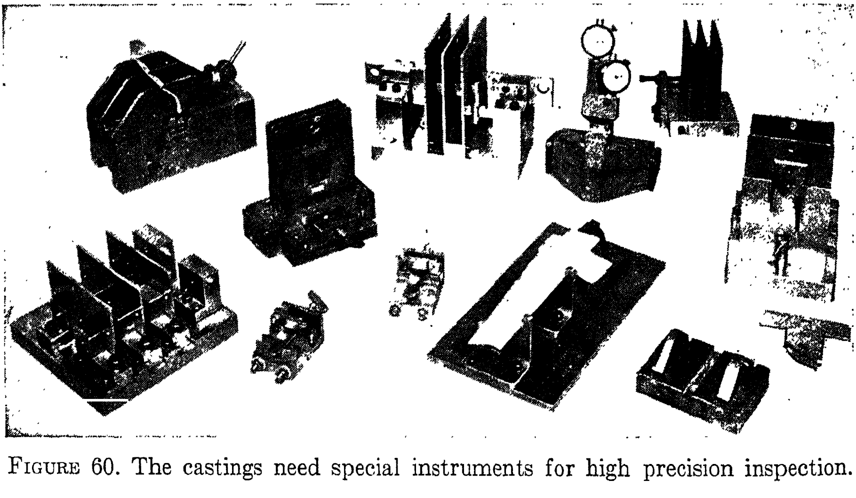


FIGURE 60. The castings need special instruments for high precision inspection.

Specific tolerances on critical dimensions and contours need not be as wide as the basic ones. The preparational accuracies for these areas can be higher. Tolerances can be narrowed on some dimensions by close control of all procedures. If necessary the net shrink can be restrained (see page 130).

The close control of specific tolerances almost always adds to production costs. Therefore it is *preferred* practice to work to basic tolerances unless specific tolerances really are needed.

Shrink which is restrained in one direction usually will go in another. Any method of holding specific tolerances on some areas also creates problems of holding the basic ones on others. Therefore, when specific tolerances must be held on some areas of the castings, it is *preferred* practice to widen the basic tolerances at other areas if the function of the product permits. The selection of these areas of widened tolerances should be discussed carefully between the product designer and the casting house. Conversations of this kind often include such statements by the casting house representative as "I'll give you plus or minus 0.0005 inch on that 0.375-inch dimension 'A' if you will give me plus or minus 0.008 inch on the location of hole 'B,' or better still, you will drill that hole." Precision investment casting does not solve all of its precision tolerance problems with the ease that some of its published literature suggests.

Groups of Basic Tolerances. For the guidance of the product designer, the casting houses can be divided into groups according to their basic tolerances. There is no standard or authority within the industry for these groupings. They are established by observation of the practices of various houses. And one house may be classifiable in one group for the casting of alloys high in castability and another for the poorly castable alloys.

Group 1. Basic tolerance is plus or minus 0.008 inch per inch, working down to plus or minus 0.002 inch on a dimension of 0.250 inch or less as its finest tolerance. This group generally casts precious or noble metals and is more interested in products of intricate contours than in close tolerances. Its principal products are jewelry and ornaments.

Group 2. Basic tolerance is plus or minus 0.004 inch per inch working down to plus or minus 0.001 inch on a dimension of 0.250 inch or less as its finest tolerance. This group in general casts ferrous alloys of high machinability and low castability and depends upon secondary machining operations when high accuracies are needed.

Group 3. Basic tolerance is plus or minus 0.003 inch per inch working down to plus or minus 0.0015 inch on a dimension of 0.50 inch; this tolerance is not reduced until a dimension on the order of 0.250 inch is wanted. At 0.250 inch the tolerance may become plus or minus 0.001 inch but this is the closest tolerance on any dimension. This group generally works with alloys which are low in castability but even lower in machinability, and with alloys of very low castability but reasonable machinability. *This is by far the largest group.*

Group 4. Basic tolerance is plus or minus 0.002 inch per inch, does not like to go below plus or minus 0.001 inch on any dimension but can get down to plus or minus 0.005 inch on occasion. This group works mostly with highly castable alloys and specializes largely upon contours which are practically impossible to generate by machining. When necessary it also produces these contours and tolerances in alloys of very low castabilities.

Group 5. Basic tolerance is plus or minus 0.001 inch per inch and can get down to plus or minus 0.00025 inch on some sections and in some alloys. Casts highly castable alloys only, and specializes in very small parts, rarely casting any dimension over 1.5 inches.

Dimensional or "Cross-Sectional Precision." These five groupings refer to outright dimensional tolerances, as, for example, measuring diametrically across a cylindrical section. Group 3 is the *preferred* practice.

There are other types of precision which have additional problems.

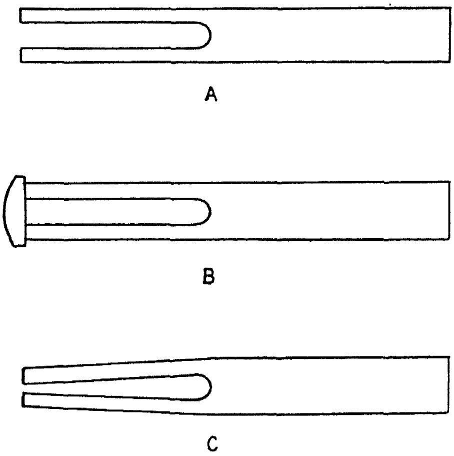


FIGURE 61. When fork shape is desired (A) a shroud sometimes is cast (B) and then machined away. The prongs on the dispensable patterns sometimes are bent inward (C) so the shrink forces will straighten them.

Parallel Precision. Two or more sections of a casting may need to be parallel. For example, the casting might be in the form of a capital "H." Here, at the junctures of the cross bar with the long bars, there would be internal angles and hot spots. Since the outsides of the long bars would tend to cool and to shrink first, those bars would tend to bow outward unless held against this.

This specific trouble can be corrected by casting shrouds across the open ends of the "H" and then machining them away, by making the dispensable patterns with the long bars bent slightly inward so the shrink of their outer surfaces pulls them straight, and by controlled slow cooling which prevents one section of the casting from cooling and shrinking at a significantly more rapid rate than another, and by other stratagems known to the casting houses. In general, the basic tolerance of parallel precision should be greater than that of outright dimensional precision.

Bowing or bending problems of this kind are known as "run-out" troubles.

Angular Precision. When, for example, a thin section connected with a thicker one is to be at an angle of exactly 30 degrees with the plane or the reference axis of the thick section, there may be run-out troubles. The causes, cures, and effects upon basic precision are the same as for parallel accuracy.

True Flatness of Planes. The problem of true flatness of planes exists in three forms. First is the question of smoothness of surface as it affects flatness. This will be discussed more fully in Chapter 9. It varies widely with alloys and with methods of removing castings from flasks.

Secondly is the problem of flatness of planes on pieces which are within or without the size or dimensional ranges preferred for this process. Here the flatness is similar in variability to the outright dimensional tolerances in thousandths of an inch per inch. But when the sectional thicknesses become greater than the preferred ones and other dimensions are in excess of the preferred ones, the variations in flatness may be accompanied by slight roundness. There is an old theory that if a cube of steel were to be annealed and re-annealed enough times it would assume the shape of a sphere. On thick-sectioned, large-dimensioned precision investment castings this procedure has some opportunity to work, first on the dispensable patterns as they cool, and secondly on the castings as they cool. The bowing rarely is enough to exceed the thousandths of an inch per inch tolerances which apply to dimensional measurements, but sometimes necessitates an inexpensive secondary machining operation.

The third problem of true flatness exists when heavy sections are continuous with light ones, and run-out problems can occur. These problems are correctable as described under parallel precision.

True Radii. The factors affecting the variabilities of radii were discussed on page 132.

When the radii in question are those of holes, the problems of shrinkage always apply to some extent unless the shrinkage is restrained at the hole contour. Where shrinkage is unrestrained but the holes are small enough and are so located that shrinkage problems are small, the minimum *preferred* basic radius tolerance is 0.008 inch per radius inch, there being no minimum actual tolerance at any hole diameter that is practical to cast.

When the radii are those of sections on the surface or the periphery of the casting, their tolerances are the thousandths of an inch per inch ones which apply to straight dimensional measurements.

Example of Threaded Straight-Section Basic Precision. Solid cylindrical pieces 0.25 inch in diameter and 2.0 inches long are to be precision investment cast with 28 threads per inch (U. S. Standard) throughout their lengths, the casting house to use no special means to increase precision, but to aim at the preferred ranges of basic precision only.

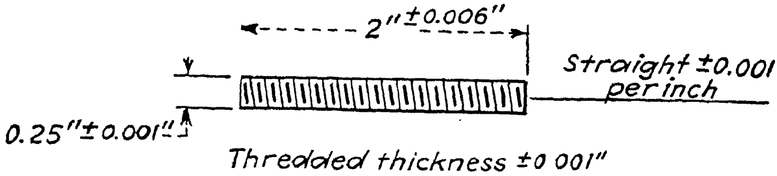


FIGURE 62. Thread accuracies on long sections usually are not equal to those obtainable by machining.

With its axis taken as a true reference line each piece could vary in straightness on the order of plus or minus 0.001 inch per inch of length. But the variations would be minor at any given point and would tend to "average out" or cancel each other; the piece would not assume the form of an arc of a circle.

The major diameter would be true to plus or minus 0.001 inch, but although this would allow a difference of 0.002 inch between any two points of measurement, it would not interfere with ordinarily good performance of the thread. The root diameter also would vary plus or minus 0.001 inch.

The cylindrical radius of the piece (out of roundness) would vary on the order of plus or minus 0.001 inch. But since it might be plus 0.001 inch at one end of a diameter and minus 0.001 inch at the opposite end of the same diameter and at various points along the length of the piece, the total error can be plus or minus 0.002 inch.

The various radii of the thread contours would vary as the smoothness of the surface, and this in turn would depend upon the alloys cast. But since such a piece ordinarily would be cast in an alloy of low castability and low machinability these variations could be expected to be on the order of at least plus or minus 0.0005 inch.

The length of the piece would vary plus or minus 0.003 inch per inch or a total of plus or minus 0.006 inch. This would be an average variation of plus or minus 0.0001 inch of lead for each individual thread. But with the variations in smoothness of surfaces of the thread contours and the fact that none of the precisions would get down to 0.0001 inch, the actual variations of lead per thread probably would equal plus or minus 0.001 inch.

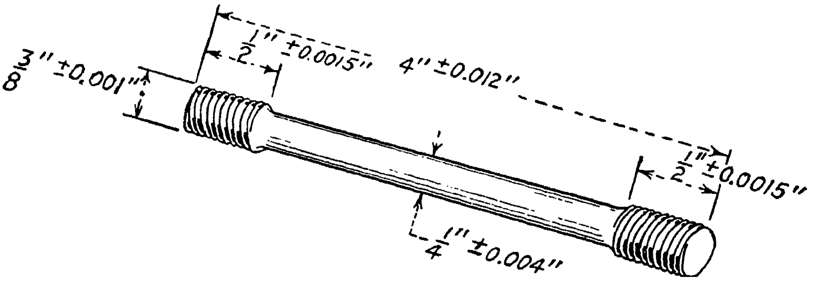
If the alloy were machinable many of these thread-lead, radius and diameter errors could be mitigated or corrected by chasing or grinding the threads as a secondary operation after casting. When the alloy is so hard as to be only slightly machinable, casting the threads and then grinding them is good practice.

It is *preferred* practice to cut long and fine threads rather than cast them. Threaded pieces of these kinds with nuts to match have been precision investment cast on a production basis of alloys of low castabilities and practically no machinabilities, the lengths being 3 inches rather than the 2 inches cited above. The nuts would travel the full lengths of the threads; no selective assembly to match threaded pieces with nuts was needed; the parts were satisfactory for their purposes. But the high spots of male and female members occasionally found each other with slight binding effects, the tight lead and loose lead errors also met, and the job in general was not equal to the threading ordinarily done by machine methods. Cast threads rarely are better than number 2 fits.

Specific Example of Selective Precision. A double-ended stud having one end threaded RH and the other LH is wanted in an alloy of low machinability. The threaded portions at each end are to be 0.375 inch in diameter and the threads are to extend 0.50 inch along them, leaving a shank section of 3.0 inches long between them. The shank is to be relieved to 0.25-inch diameter.

Close tolerances are wanted at the threaded ends. The tolerances of the relief section are less important so long as the relief is there.

If preferred ranges of basic precision alone are used, the diameters of the threaded sections will come to plus or minus 0.002 inch, their lengths to plus or minus 0.002 inch, and the diameter of the shank to plus or minus 0.001 inch. The cylindrical radius at the threaded ends might come to plus or minus 0.001 inch but probably would be nearer 0.0015 inch, thus permitting an out-of-roundness error up to 0.003 inch. This procedure, of course, would put the highest precision at the shank diameter where it is least needed.



Hold this 1/4" dimension too close and the important ones must be given larger tolerances

FIGURE 63. Double-ended stud.

Length would come to plus or minus 0.012 inch. It is assumed that this would be satisfactory, or if unsatisfactory the piece could be cast a few thousandths longer and the correct length obtained by a simple fixture grinding operation costing less than a quarter of a cent per piece.

If the designer permits the shank diameter to come to plus or minus 0.003 inch, or even better, permits the casting house to go to 0.004 inch as the extreme limit but to aim at plus or minus 0.003 inch as the shop production standard, the precision of the critical end sections can be much higher.

The pieces then can be gated quite readily from the sides of the shanks using two gates not more than 1.25 inches apart. This will mean that the ends will be the starting points of a great deal of the progressive deposition of the metal and that by careful clustering of the dispensable patterns and wise design of the contours of the invested flask, the cooling rates of the critical ends can be controlled closely.

With these methods, plus putting nearly all of the costs of preparational accuracy into those critical end sections, the threaded ends easily can be brought to plus or minus 0.001 inch on their diameters, plus or minus 0.0015 inch on their lengths and plus or minus

0.00075 inch on the diametral radius. These tolerances can be tightened still further if necessary.

Another effect of the side gating would be to decrease the likelihood of dendritic cracks in the shank. This would mean a slight increase in tensile strength but a great increase of elongation under tensile test of the piece.

If higher accuracy of the shank were necessary it could be cast to the top limits of its tolerance, the gates hand-ground flush with the surface, and a secondary centerless grinding operation used at low cost to obtain final accuracy.

Pieces of this kind have been precision investment cast in large quantities. Machined from the solid and from hard metals which are low in machinability and with one RH and one LH thread, they cost more than do the precision investment castings.

Gears and Gear Teeth. Gears and gear teeth and similar shapes often are used as illustrations of the precision investment casting process. In actual fact, highly developed and organized special machine tools exist for cutting these shapes at very low unit costs, and these tools usually produce at lower costs than are available by precision investment casting. When gear shapes can be cut, it is *preferred* practice to cut them.

In some instances specially contoured hubs and webs are wanted and precision investment casting is the most economical way of producing them. In these instances it is *preferred* practice to precision investment cast the necessary gear blanks and then machine-cut the teeth.

Gears often are wanted of alloys of low machinability. *Preferred* practice is to precision investment cast the tooth shapes slightly oversize and then either machine or grind them to shape. Much depends upon the operating speeds of the gears and upon their pitch diameters. Precision investment casting, especially in alloys of low castabilities, does not ordinarily produce surfaces adequate for low noise level operation at high speeds. And with pitch lines varying, at preferred ranges of basic precision investment casting precision, on the order of plus or minus 0.003 inch per inch, this factor also is inadequate for high speed operation. But where the hard alloy gears are wanted for slow speed operation, as in gears that endure high temperatures while actuating materials-handling devices that travel through furnaces or salt baths, the as-cast accuracy may be as adequate as the as-fabricated.

Gears of highly special tooth contours, or having teeth at angles to the gear axis which are difficult to handle in standard gear cutting machines, or having teeth in such positions that it is difficult or impossible for cutting tools to work on them without machining through solid sections which are wanted intact for the functioning of the product, often are precision investment cast. These types usually are cast of highly castable alloys in which the smoothest surfaces and highest accuracies of the process are easiest to obtain.

Many of these special types, before they were precision investment cast, were made of shapes which allowed for the tooth cutting of some members and for machining others to size, after which they were assembled by brazing or welding. Precision investment casting has proven both less costly and more satisfactory.

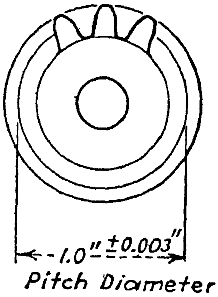


FIGURE 64. Gears, unless special, should be machined.

Example of Gear Casting. Gears of an ordinary spur type having pitch diameters of slightly over 1.0 inch are to be cast to tolerances of the medium range preferred for the process. The pitch diameter would be true to plus or minus 0.003 inch but the concentricity as measured from the bore center as a reference line would be plus or minus 0.0015 inch.

The various radii of the tooth shapes would have tolerances on the order of 0.0015 inch or perhaps 0.002 inch. The errors of circular pitch would not include the graduated increments sometimes found in cut gears, increments which cause the "first" tooth to be the thickest and the "last" tooth, which is beside the first, to be thinnest. That is, these increment errors would not occur unless they were committed in making the mold for the dispensable patterns. As-cast errors of circular pitch would be scattered at random about the pitch line. Their magnitudes would depend largely upon the surface finish possible to obtain with the alloy cast, but no tolerance anywhere on the gear could be expected to be finer than plus or minus 0.001 inch.

Closer pitch diameter tolerances could be held but are not preferred practices.

Example of Perforated Disc. A disc 5 inches in diameter such as might be used as the ball spacer or retainer for a flat-raced ball thrust bearing is to be cast to the precision preferred for the process. Perforations of 0.0625-inch diameter are to be cored into this disc to receive the balls. The perforations are to be arranged in circles which will be as concentric with the bore as the preferred range of precision will bring them. The first such circle is to be 1 inch in diameter and each successive ring is to be 1 inch larger in diameter.

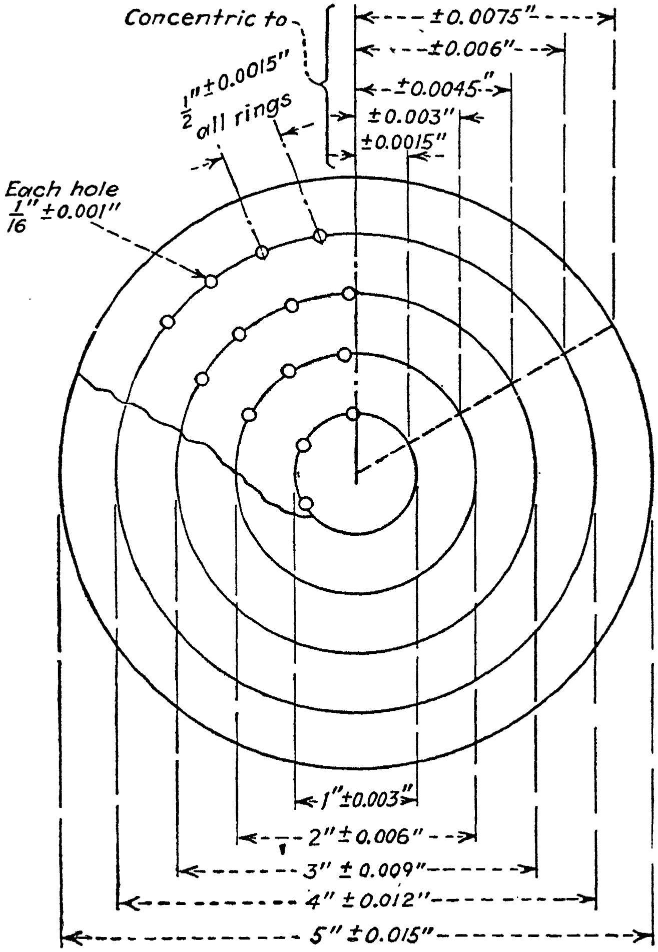


FIGURE 65. Schematic example of a perforated disc.

The perforations are to be 0.50 inch apart as measured along any ring.

Each of these perforations will have plenty of solid metal around it, therefore distortion should be slight and any variation from true radius within any perforation will mostly be a function of the surface smoothness possible to obtain with the alloy selected for casting. If the alloy is highly castable this radius could be true within plus or minus 0.0005 inch. But this tolerance would depend upon the preparational accuracy, as would the diametral tolerances of the perforations. This diametral tolerance could be held to plus or minus 0.001 inch or twice the tolerance of the radius.

The first circle of perforations would have a radius of 0.50 inch from the true center of the disc and therefore a concentricity on the order of plus or minus 0.0015 inch. The concentricity of the second ring would be on the order of plus or minus 0.003 inch. Each successive ring would have a concentricity tolerance increase of plus or minus 0.0015 inch. In a product intended for the function of this one, the tolerance increase would have good effects rather than bad since it would mean that very few balls would traverse exactly the same paths on the races and that the races would wear more slowly accordingly.

The balls would be spaced to center distances as measured along their own rings with tolerances of plus or minus 0.0015 inch.

If this part were to be made of reasonably castable alloy so that sound metal could be expected throughout, and the alloy were reasonably machinable, it would be preferred practice to core-in only one of the perforations and use it as a guide hole for a gang drill. The exception to this would be an instance in which too few parts were wanted to warrant the cost of a gang drill, in which case the perforations might be cored in.

If the alloy were low in castability so that shrink porosity could be expected, the perforations might be cored-in and little attention paid to their preparational accuracies since each perforation would be a guide hole for a single-spindle sensitive drill and the perforated casting would act as its own drill jig.

Likewise, if the alloy were so poor in machinability that the power supply troubles and the drill breakage troubles of a gang drill would be costly, it might be preferred practice to core in the holes and have the part act as its own drill jig.

Tapered Piece Example. A piece is to be cast to the precision preferred for the process, the piece to be in right angle triangular form with one leg 1.0 inch long, the other leg 3.0 inches long, the hypotenuse to serve as the taper.

The point of the taper, of course, would be the critical area. This could be as thin as 0.015 inch plus or minus 0.001 inch if in an alloy of low castability, or 0.005 inch plus or minus 0.0005 inch if in a highly castable alloy.

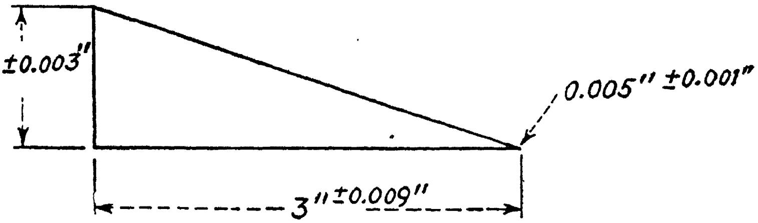


FIGURE 66. Tapered piece at ordinary tolerances.

The length would vary by plus or minus 0.009 inch and the height by plus or minus 0.003 inch so that the combinations of these two variables could make significant differences in the degree of taper if high accuracy taper were wanted.

A piece of these contours would be machined in most instances, or if wanted in an alloy of very low machinability or in a metallurgical structure having the high vibration-dampening abilities of the cast structure it might be precision investment cast and then machined or ground to true accuracies. The example is cited because it is a simplification of typical problems which occur in many designs, especially of products which are to endure high temperatures.

Solid vs Hollow Structure Example. A piece is wanted 2.0 inches long by 1.0 inch wide by 0.50 inch high, to be cast to the precision ranges preferred for the process. The alloy desired is of low machinability, low fabricatability by rolling processes and therefore rarely rolled into bar stock, and of a composition too seldom wanted to warrant making a special run at the steel mill. Precision investment casting therefore is indicated.

Decision would have to be made as to whether or not to permit a slight draft. Precision investment casting does not need pattern draft for removing patterns from investments. But the preparational costs for making the dispensable patterns sometimes are reduced by allowing a draft on the order of 0.001 inch per inch to assist in getting the dispensable patterns out of their molds.

The basic precision tolerances of the piece would be plus or minus 0.006 inch on the length, plus or minus 0.003 inch on the width and plus or minus 0.0015 inch on the height. But as-cast in the solid, a piece of this thickness would have some tendency to form curvilinear contours on its major planes and perhaps on some of its minor ones (see page 137).

To avoid this tendency and to reduce weight this piece could be redesigned to have two cored-in passages extending throughout its length. The piece then would resemble an open ended box having a supporting wall down its middle. The wall thicknesses would be anything over 0.040 inch plus or minus 0.001 inch. Basic outside tolerances would be unchanged unless the cost of using uncrushable cores were warranted, in which case these tolerances could at least be cut in half (see page 129).

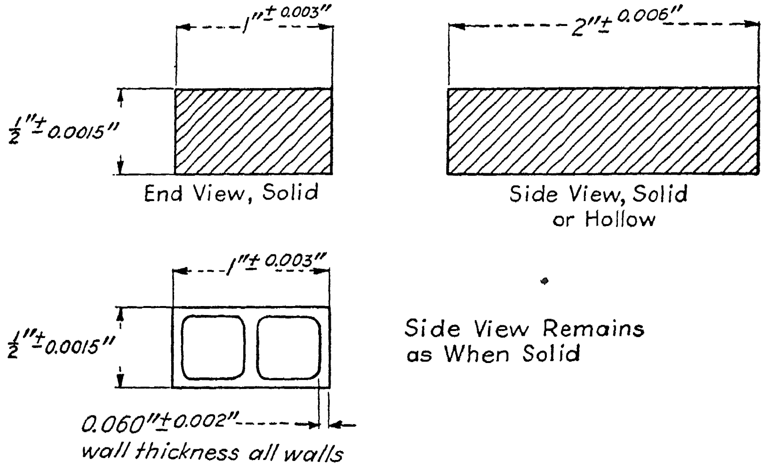


FIGURE 67. Hollow sections can be better than solid ones.

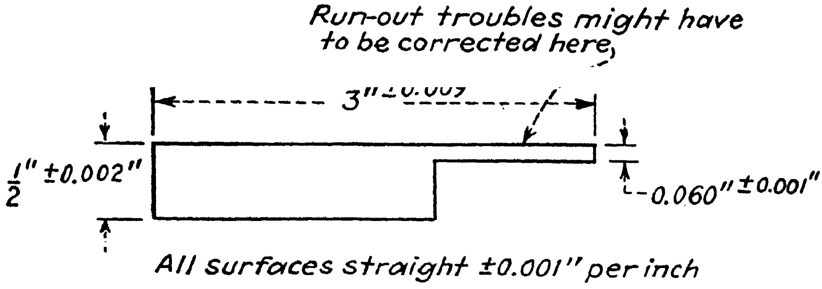

Run-out troubles might have to be corrected here
3"±0.009
½" ±0.002"
0.060"±0.001"
All surfaces straight ±0.001" per inch

FIGURE 68. The internal angle might better be ribbed or filleted.

Example of Thin Section Continuous with Thick One. A piece having a longest dimension 3.0 inches long, a width of 0.50 inch, the wide section to extend 2.0 inches lengthwise of the piece and then to have abrupt 90-degree transition to a section only 0.060 inch wide, three planes of this thin section to be continuous with three planes of the long dimension, is to be precision investment cast to the tolerance range preferred for the process.

Tolerance on the length would be plus or minus 0.009 inch, on the width plus or minus 0.002 inch, and on the width of the 0.060-inch section plus or minus 0.001 inch. There would be run-out troubles at the thin section (see page 136).

A fillet would be helpful at the interior angle where the thin section joins the thick one. If the alloy were sufficiently machinable and a true 90-degree angle were wanted at that point, this fillet could be removed by an inexpensive secondary machining operation.

Pieces of such contours, and with all surfaces intended to be flat, are not ordinarily precision investment cast. But the example is an excellent illustration of a run-out problem which often is found in casting design. And if the alloy were relatively unmachinable, and it was desired to reduce the weight of the heavy section, precision investment casting could core-out that section and make it hollow, or could cast channel shapes into any or all of the heavy section planes. When these stratagems are desired in the designs, products of the general contours described here very often are precision investment cast.

Chapter 9

Surfaces

The surface finishes of precision investment castings can be of two kinds: (1) as-cast, and (2) as-finished.

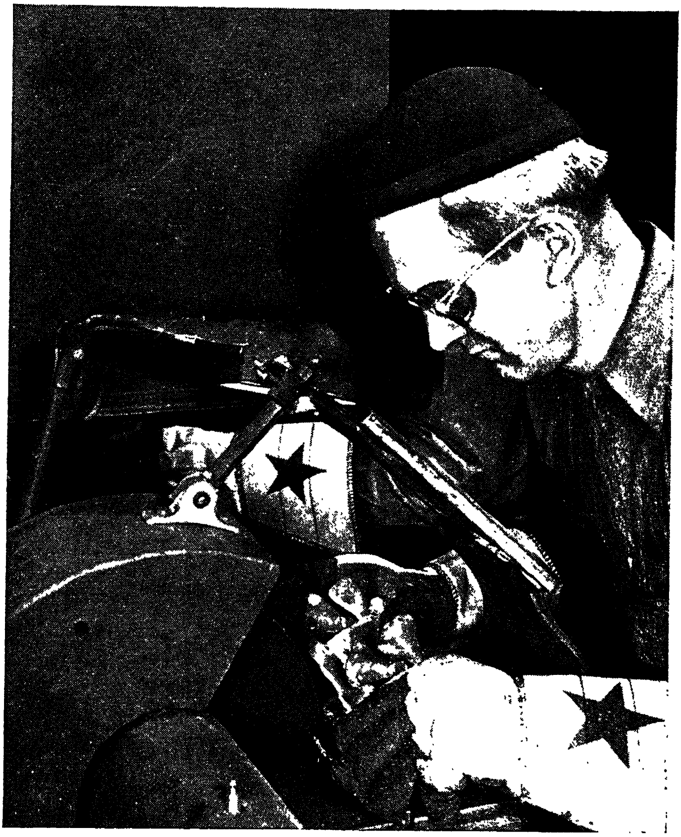
As-Cast Surfaces. As-cast surfaces are those which have not been altered in any way with the exception of grinding or machining off the gate or sprue extension. Such surfaces are commercially obtainable only on alloys which can be cast into investments which can be removed from the castings by dissolving in water or otherwise without shot- or grit blasting or any other forceful mechanical action. These surfaces are obtainable, in general, only in some of the nonferrous alloys such as precious metals and copper alloys.

The typical as-cast surface has a beautiful matte appearance. It can be plated to a beautiful satin finish, or with some alloys can be directly polished to such a finish. But it is not completely uniform. It always has at least one area from which the gate has been removed (there sometimes are two or more gates per casting) and this area has a machined or ground appearance which differs from the remainder of the surface.

In some instances the gate area can be so placed as to be inconspicuous in the completed product. But the selection of the gate area is one of the most critical matters in the planning of the casting procedure. The position of the gate or gates has important bearing on the progressive deposition of the cast alloy and upon the number of castings which can be geometrically arranged to be produced in a single flask. Therefore this position affects both the quality and the cost of the finished castings. Also, in many instances the grinding-off of the gate extension is made a combined operation for securing the desired accuracy of a dimension which must be held to closer tolerances than precision investment casting ordinarily can deliver, and the gate has to be placed where this can be done. And altogether, effect upon the surface appearance of the product is the last matter considered when selecting the gate area or areas.

It is *preferred* practice to have all surfaces as-finished.

As-Finished Surfaces. Investments of the kinds commonly used for ferrous alloys and for many other alloys cannot be removed without the use of physical force, on a commercial scale. For laboratory and control inspection purposes such removal can be done at the casting house with the use of very little physical force, but this operation is individual for each casting and is costly.



(Courtesy Haynes Stellite Co., Kokomo, Ind.)

FIGURE 69. Unless the piece is finally finished to an even texture there will be a distinctive area where the gate is ground off.

The physical force affects the appearance of the surface. The effects are subject to control in high degree. Various effects can be had at will. But since the common last step is the use of grit- or shot blasting, the basic surface obtained is "as-blasted." The appearance and to some degree the nature of this surface can be controlled by varying the grit or shot size and the method of blasting.

It is *preferred* practice, that when the basic as-finished surface is to be supplied, the casting house and the product designer should agree upon a specification for grit or shot size to be used, and have the casting house supply samples finished in the agreed manner. Some of the samples should be kept by the casting house and others by the purchaser or product designer. These samples should be the measures or comparison pieces by which the surfaces of production runs of precision investment castings are to be judged.

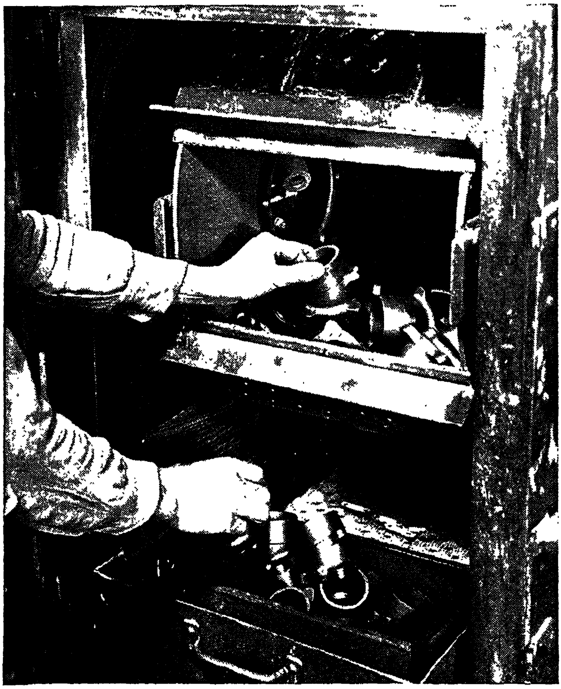


FIGURE 70. The average finish is "as-blasted."

Other Finishing Methods. Precision investment castings also can be submitted to secondary finishing methods such as scratch brushing, tumbling, electropolishing, salt bath descaling or plating, or any other methods common to metals finishing. The casting houses have facilities for some of these and can have others performed on contract if desired.

It is *preferred* practice that when the casting house is to supply surface finishes which require any secondary operations, the casting house should supply actual samples of these finishes. The samples are the comparison or test pieces by which production runs of precision investment castings are to be judged.

Parting Lines

Parting lines can exist on precision investment castings but they are vestigial as compared to those on sand castings or to the flash on die castings or on forgings. Parting lines are produced when separating the molds for removal of the dispensable patterns. They can be eliminated from the patterns, but usually at a higher cost per casting than would be paid for grinding them from the castings. In many instances they can be so placed as to be concealed in the assembly of which the cast product is a component, and in most cases they have no effect whatever upon the functional economy of the product.

Surface Imperfections

The great majority of as-finished surfaces on precision investment castings are completely adequate for the functions of the products. There are rare instances in which the products are exposed to such heavy stresses or such severe conditions of abrasion, corrosion or other conditions that special attention must be paid to surface perfections. It is *preferred* practice to solve these problems by the use of more resistive alloys or by better functional design of the product. But if this practice cannot be followed, special attention may be needed for the elimination of surface imperfections.

Types of Surface Imperfections. Surface imperfections may be caused by slight imperfections in the surfaces of the investments, by chemical reaction between the cast alloy and the investment material, by chemical or physical reaction between the alloy and the air which is entrapped within the air-permeable structure of the investment, and by low castabilities of alloys.

Any of these troubles, or several of them in combination, may cause surfaces to be physically faulty, or chemically faulty.

It is *preferred* practice to specify surfaces in terms of faults permitted and forbidden, and to build such specifications upon the basis of the functional economy of the product (see Chapter 5).

Physical Faults. Possible physical faults include surface porosities, hot tears, scabs or loose areas which will flake off, roughness, and blisters. Blisters are actual bubbles of metal which can form and solidify on the surfaces.

Chemical Faults. Possible chemical faults include oxidations, decarburizations, and chemical reactions between the alloys and the investment materials.

Minute segregations of metals or alloys or metallurgical structures of alloys on surfaces usually are called chemical faults but sometimes are called metallurgical faults.

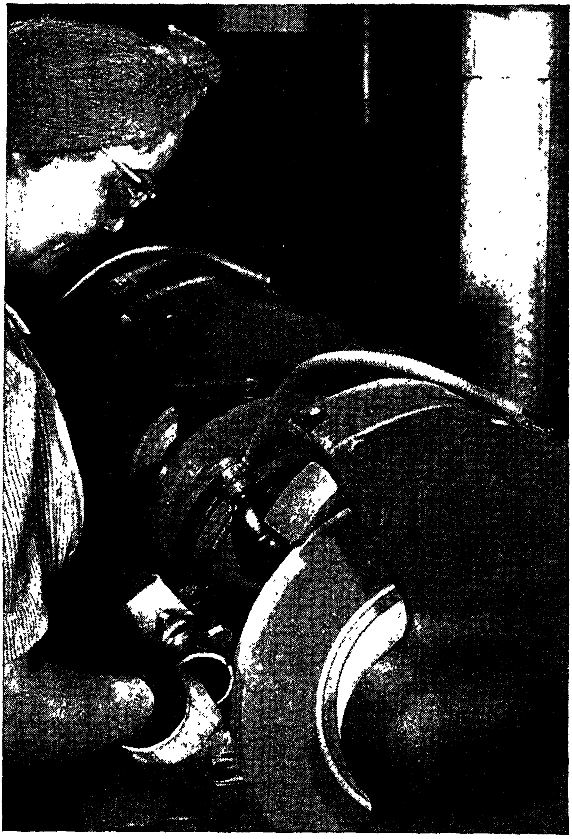


FIGURE 71. Surface imperfections may need special surfacing operations.

Effects upon Strength. Surface faults can become stress risers and cause failures under severe loads of any kind and especially can cause fatigue failures under severe vibrational loads. As-cast metallurgical structures tend to have millions of tiny stress risers between the crystals of their structures, and therefore tend to distribute such stresses and not to be so subject to bad effects of stress risers on their surfaces as are as-wrought structures. But on rare occasions precision investment castings are so stressed that this problem exists.

The surface alloy of precision investment castings tends to be the first to solidify and deposit and to be the starting area for progressive deposition. Therefore this surface alloy tends to be the area least subject to segregation and altogether the "best" alloy. But if the alloy is subject to any surface imperfections whatever, the "best" alloy may consist of a secondary layer immediately below the outside layer.

When high strength is desired, the removal of surface imperfections never should be permitted to go deep enough to remove this "best" layer. This is a subject which may need careful discussion between the metallurgists of the product designer and the casting house. The depth of this "skin effect" varies widely with differing alloys and casting methods. But tests made by removing layers 0.001 inch at a time and then making physical strength measurements have suggested that the strength in psi usually increases until about 0.006-inch depth of surface has been removed, after which that strength begins to decrease.

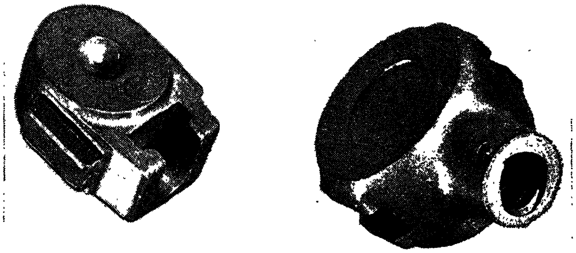


FIGURE 72. Stainless steel (18–8) globe valve wedges must have high precision surfaces.

Therefore, it is *preferred* practice that special agreements be made as to the depths to which surface metal may be cut away in removing surface imperfections when the purpose is to eliminate stress risers. But in the absence of such agreement it is suggested that 0.006 inch may be a good limitation.

Effects upon Corrosion Resistance. Either the as-cast or as-finished surface may be more resistant or less resistant than the other, as between two alloys or even two mild variants of the same alloy, when exposed to the same corrosive agent. Some alloys are resistant to some corrosive agents only when in the as-polished or the as-passivated conditions. For further information on the highly complex subject of corrosion resistance, the reader is referred to the extensive literature on the subject.

When minute segregations, such as those of free ferrite (sometimes found upon the surfaces of stainless steels which have been subject to grit blasting or to any scale-removing operation whatever other than acid pickling), are promoters of corrosion, they must be removed by pickling or by other appropriate and effective means either in the plant of the casting house or in that of the product designer.

Precision investment casting prefers to meet corrosion problems by the use of alloys which are higher in their resistances to specific corrosive agents than are the alloys commonly used as-fabricated for the same end products. But if this stratagem is not employed, each corrosion resistance problem must be solved upon the basis of its own factors.

Investigation should be made as to whether or not the same "best metal under skin" exists for corrosion resistance as for high strength in the instances of specific alloys.

The ability of this process sometimes to cause one element or one metallurgical structure of an alloy to coat an entire casting or to be heavily concentrated at specific surface areas of castings should not be completely overlooked when considering corrosion resistances of surfaces. See pages 104 and 105.

Corrosion resistance often needs to be more than a surface property. Under some corrosive agents or conditions it is to be taken for granted that corrosion will take place and that the important factor will be the rate at which corrosion progressively weakens or destroys a product. These conditions are to be met by superior alloys and superior metallurgical conditions of alloys, both of which precision investment casting can supply.

Deep resistance, or even surface resistance, to corrosion can be affected by very fine segregations or precipitations within alloy products. A commonly cited, although not commonly existing, example of this is the precipitation of carbides between the crystals of improperly heat-treated 18–8 stainless steels, the corrosive agents being able to attack these precipitations with resultant intergranular corrosion and weakening of the alloy. Another example is the segregation of free ferrite which can occur even in some of the high alloys. A third is the setting up of surface segregations which, however infinitesimal, are capable under thermal, or other changes, of becoming positive and negative poles between which electrical currents will flow. These currents create conditions which promote corrosion. In fact, surface segregations which either are low in corrosion resistance or set up electric currents which promote corrosion, often are the starting points of corrosion which otherwise would not occur and as such are called "rust triggers." Once it is "triggered," this corrosion may spread widely over a surface and penetrate deeply into the piece.

Corrosion may be planned to take place at a surface and to become self-inhibiting immediately below the surface. Common gray iron can form a somewhat deep self-inhibiting corrosion. Stainless steel forms a corrosion-inhibiting oxidized layer which is so thin that it interferes neither with high surface hardness, high accuracy nor high polish.

Precision investment casting by varying its alloys, its heat-treatments and its surface treatments, can meet nearly any corrosion problems which can be met by metals at all. But when recommending an alloy for such a problem the casting house must know: *What degree of corrosion resistance is wanted, to what corrosive agent, under what operating conditions?*

Abrasion Resistance

Abrasion resistance can exist in several forms. These forms may exist singly or in combinations. By wise selections of alloys and procedures precision investment castings can have all of these resistances. Some of the forms are:

(1) *Outright hardness of surface,* as in the ability of a case-hardened steel to resist wear.

(2) *Deep and through hardness,* as in the ability of cobalt alloy or a through-hardened steel to persist in wear resistance after its surface is worn through.

(3) *Anti-weldant qualities,* as in the abilities of some alloys and some surfaces to resist welding between tools and chips or between materials under high temperatures and heavy pressures.

(4) *Embeddabilities,* as in the abilities of some bearings alloys to embed themselves with hard particles carried by lubricants rather than being abraded by those particles.

(5) *Lubricities,* as in the abilities of nearly all cast structures to increase the lubricities of lubricants. Some precision investment cast alloys likewise are high in materials having high lubricities such as free carbon, lead and aluminum.

(6) *Surface shear-abilities and wipe-abilities.* There are no specific technical terms to describe these properties. But some hard alloys are subject to having minute surface projections fracture or shear off, producing extremely smooth surfaces high in abrasion resistances. Tougher

alloys can have these projections spread or "wiped" across their surfaces, producing the same effects. Both types are "abrasion inhibiting."

(7) *Lubricant storage abilities.* Porous alloys can store lubricants. Alloys vary widely in their abilities to absorb lubricants into their surfaces for boundary lubrication; the smoothness of surface also affects this, superfinished surfaces having less of this ability.

(8) *Thermal expansion coefficient.* Alloys high in thermal expansion tend to press themselves toward the abrasive agent under the frictional heat of abrasion, and thus under some circumstances to promote their own abrasion.

(9) *Thermal expansion absorption.* Some alloys and metallurgical structures have porous structures or soft and free intergranular components into which some of the friction-induced thermal expansion can go, thus reducing the ability of such expansion to promote abrasion.

(10) *Thermal endurance.* Some alloys weaken rapidly under the heat of abrasive friction, others separate intergranularly ("grinding cracks" formed when grinding some hard alloys are examples of this) and thus create "trigger areas" of ready attack for further abrasion. Others are high in thermal endurance.

(11) *Vibration absorption.* Abrasive friction commonly causes high frequency vibrations, the familiar "squeals and groans" of friction. These vibrations are promoters of abrasion and increasers of the thermal expansions which also promote abrasion. All cast structures in general are highly dampening to vibration, but those of some alloys which contain soft elements interspersed with harder ones are especially so. Porous cast structures also can be high in their dampening effects.

(12) *Corrosion and abrasion.* These factors are natural allies for the attack upon any product.

As was learned decades ago by makers of bearings, slides, guides and other products which must resist abrasion, surface hardness alone is very far from being a good criterion of ability to endure abrasion. Precision investment casting undoubtedly can produce more forms of abrasion resistance and in more combinations than any other process. But in handling this problem the casting house must ask such questions as: *What kind of abrasion, produced by what abrasive agents, to be resisted to what extent and by what forms of abrasion-resistant properties?*

Where surface resistance to abrasion is solely a problem of surface hardness, it may be *preferred* practice to specify that no surface finishing operation shall get below the "best metal under skin," if such a skin exists with the alloy in question, as discussed in this chapter. See page 153.

Where surface shear-abilities and wipe-abilities exist they are likely to be in the as-cast or as-blasted extreme outer skins and should not be removed. Such surfaces sometimes are described as having "break-in abilities" in that they permit a product to conform to the contours of mating parts which move in relation to it, after which the surfaces become abrasion or wear inhibiting. Many of the hardest steel tools now are deliberately given softened or blued surfaces for break-in abilities.

FIGURE 73. Precision investment castings of Stellite and other hard alloys are abrasion resistant throughout their cross sections.

Embeddability also may be greatest in the as-cast or as-blasted surface. Extremely hard particles which embed themselves in a surface often become protective to the surface and make the surface abrasion-inhibiting. The presence of embeddable particles often is greatest during the break-in period; therefore embeddability and break-in ability often must accompany each other in the same as-cast or as-blasted surface.

Machinable Surfaces

It is rare for precision investment casting to work deliberately toward machinability of its alloys, although this may be done when some intricate contours are to be as-cast and others are to be machined from the solid, as in the making of special gears and sprockets. But a great many surfaces are machine-finished from the as-cast or as-finished states. Examples are the chasing of cast threads, the drilling out of cored holes.

Many of these machined surfaces are in areas where imperfections of cast surfaces are most likely to occur. For example, any air which is entrapped in the pores of the investment under the pressure of the entering molten metal will seek to escape by the path of least resistance, and on interior intricate contours such as female threads, that path may be toward the solidifying metal. Where the resulting imperfections cannot interfere with machining nor reduce the quality of the machined surfaces, it is needlessly costly to specify that the casting house shall scrap good castings on which such imperfections are found or shall employ intricate techniques to prevent them.

It is *preferred* practice, therefore, that when surfaces are to be machined or are to be corrected by machining or other secondary operations, the surface specification shall be no more than that those surfaces shall contain no imperfections sufficient to interfere with the secondary operations or to affect the quality of the completely finished surfaces.

Where machining must be done, precision investment castings ordinarily will not be found to suffer from the "hard and abrasive skin" troubles common to sand castings. The skin effects of precision investment castings vary with alloys and with casting procedures, but very rarely are such as to interfere with extremely fine and highly accurate machining.

Surface Detail

The fineness of surface detail which precision investment casting can reproduce varies with the castabilities of alloys. In fact, there is no design feature in which castabilities are more important.

The obtainable surface detail should be considered in several categories:

(1) As-cast in highly castable alloys.
(2) As-blasted in less castable alloys.
(3) As-finished in alloys of very low castabilities.
(4) As-finished when special finishes are required.

As-Cast. In highly castable alloys from which the investments can be removed without forcible means the most delicate lines of the engine turnings on a fine watch case can be reproduced. No one seems to have measured to find out what the limitations are, but the only apparent limit of detail fineness with the most castable alloys seems to be the grain or particle size of the investment and the resultant contours into which or about which the particles could fit themselves. And since some investments now have particles so fine that sieves are useless for classifying them and they must be separated from coarser particles by air flotation, it is apparent that the reproduced details can be very fine indeed.

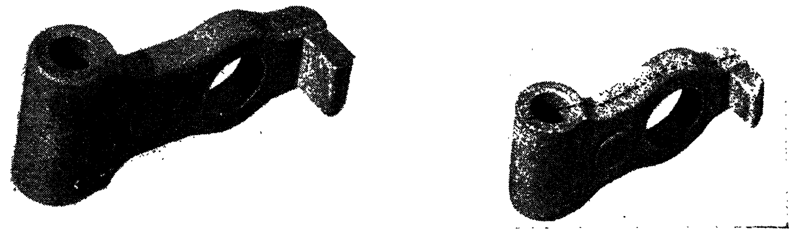


FIGURE 74. Valve check hangers of naval bronze preserve fine detail on as-blasted surface.

As-Blasted. When forceful means such as grit-blasting are needed for removing investments, those means always have tendencies to attack fine edges and other fine details. And since for any investment which must be removed by force, the less forceful (more gentle) the means, the higher the operating cost, the problem of the fineness of the detail which can be preserved is largely one of the economic or product function value of preserving it.

There are alloys of low castabilities which do not need forceful means to remove their investments, and alloys of high castabilities which do. But in general the alloys which need forceful means are of somewhat low castabilities.

The two handicaps work together. Alloys of low castabilities will not wet out (will not "follow") extremely fine details in the surfaces of their investments, therefore those details cannot be cast into their surfaces. And if the details were cast in, they probably would be blasted off while removing the investments.

As-Finished in Alloys of Very Low Castabilities. As the castabilities of alloys become progressively lower, their wetting-out abilities in terms of ability to follow fine details of investment surfaces, in general, become progressively lower. Also, in general, the particle finenesses of investment materials practical to use with them, and the fineness of details which can be molded with those particles, become progressively lower. The tendencies of alloys to form surface scabs, blisters, deep pits or porosities and other blemishes which must be machined or ground away increase as castabilities become low.

Opposed to this are a few alloys which are highly castable in regard to surface details but have low castabilities in other respects. Such alloys may be highly liable to hot tears at interior or re-entrant angles, to have wide mushy ranges, be subject to gas porosity at their interiors, or otherwise be troublesome. The castability of such an alloy for perfection of surface detail depends upon the contours of the product and the functional need of the product for strength.

As-Finished When Special Finishes Are Required. Precision investment cast products may require pickling to make them completely corrosion-safe for their functions. An example of this is the need to pickle some stainless steels when the are to be exposed to some corrosive agents, in order to remove any "rust trigger" free ferrite from as-blasted or even as-cast surfaces. Pickling acids always tend to attack sharp corners. In so doing, the acids modify the sharpness of detail obtainable in the finished product.

Electropolishing (reverse electroplating) can clean up some surfaces by causing protruding metallic particles to be "plated off." In fact, this is the purpose of the process and the method by which it smoothens and polishes surfaces. But it also attacks sharp corners and modifies the fineness of detail obtainable in the finished product.

Abrasive polishing with tripoli or any other medium attacks sharp edges to some degree. That degree is subject to close control, and precision investment casting can utilize alloys which tend to hold their sharpnesses of detail and promote the controllability of the polishing process. Nevertheless polishing does modify the obtainable sharpness of detail. As with the products of any other process, experiment may be needed to produce the original surfaces which, with further experiments with polishing techniques, will result in the desired as-polished finishes.

Plating has some tendency to build up on sharp corners, and some tendency to fill up fine indentations, dependent upon the plating alloy and the plating technique. In either instance it modifies, at least to some degree, the sharpness of obtainable detail.

For further data upon plating the product designer is referred to the extremely extensive literature. But the ability of precision investment casting to provide alloys of high affinities for plating metals is not described in the literature since very little work has been done in the study of these alloys in their precision investment cast states. A great many plating difficulties arise from the fact that metals which are intricate to plate have to be plated onto alloys which were tailored (see Chapter 7) for stamping or machining or other production processes and that these alloys never were compounded with their plate-abilities as foremost considerations. Precision investment casting very often can make plate-ability a foremost consideration in the compounding of an alloy, and can do so without sacrificing other qualities desired for the function of the product.

Quite a few protective and even decorative plating operations can be eliminated by precision investment casting alloys which provide the same effects without plating. This may result in improving the product without increasing its cost.

When either polishing or plating is to be done, the porosity of the cast surface may be highly important. Porosity specifications of this type are extremely difficult to write in specific terms of sizes, shapes, depths and numbers of pores permissible per square inch. Such a specification adumbrates (presumes and predicts) that a specially equipped microscope is to be used for counting and measuring the pores. It is, therefore, *preferred* practice that when precision investment castings are to be polished or plated, the polishing or plating method shall be specified to the casting house, samples in the as-polished or as-plated state shall be set up as standards or criteria of quality of finish, and any castings which cannot be finished to equal those samples shall be considered defective.

Molten metal spraying (metallizing) can be done readily on precision investment castings. This process as applied to machined surfaces commonly needs special surface treatment either by scoring the surface or by making rough weld metal deposits in order to bond the sprayed metal. Precision investment casting can provide ideal surfaces for such bonding and without the costs of any special surfacing operations. And although precision investment casting prefers to achieve by selection of alloy ingredients the effects usually obtained by metallizing, there are instances in which metallizing can give bearing qualities, can close porosities before polishing or plating, add hardness of surfaces, or impart other surface properties to better advantage than can alloy selection alone. In some products the precision investment casting surfaces should be metallized to match the appearances of surrounding parts which must be metallized.

Some products are electroplated or metallized and then given special heat-treatments which cause the surface and the body metals to alloy at the surface. For example, copper parts for high-temperature heat exchangers are said to have their endurances greatly increased if first thickly coated with aluminum and then heat-treated for 1 hour at 1600 degrees F, the heat-treatment causing the aluminum and copper to fuse into an alloy which is highly protective at service temperatures up to 2200 degrees F. Precision investment casting prefers to substitute alloys which are in themselves sufficiently protective, but in the instances where the surfacing followed by heat-treating offers superior protection, precision investment casting can supply alloys which are highly amenable to the treatment and which reduce the costs of treating.

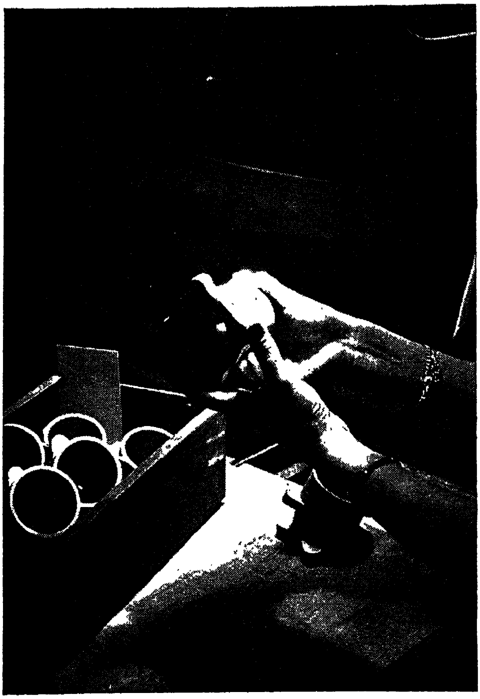


FIGURE 75. Zyglo oil plus black light reveal surface imperfections which might interfere with finishing.

(Courtesy Haynes Stellite Co., Kokomo, Ind.)

Precision investment casting also can provide surfaces specially adaptable for painting, lacquering, enameling or any other finishing processes.

Metallizing or any other thick coating processes assumes that no as-cast surface detail will be wanted which will be obliterated by the coating. In a great many products in which these coating processes have been considered inescapable, precision investment casting can work with alloys which do not need them. By this means amazing improvements in the appearance and the functional economies of product designs may be made.

Precision investment castings can be descaled by salt bath or other methods. But the need to do so proves that there has been some factor in the alloy selected, or in the heat-treatment while the castings were in the investments or after removing them, which has caused so heavy a scale that it needs to be removed. Where these conditions exist, as they must in some products which are so highly stressed that the ultimates of their "physicals" must be developed, the limit of surface detail obtainable is largely established by the obliterating effects of the descaling. The descaling process may not attack sharp edges or cause similar damage. But the scale itself is likely to be thickest at sharp corners or at areas of fine surface detail and when the scale comes off the fine detail comes with it.

The Overall Picture. In highly castable alloys surface details with fineness on the order of 0.0001 inch and perhaps even finer may be obtained. As alloys become less castable the limits of surface details become coarser until their fineness is on the order of 0.002 inch or so. If surfacing operations such as polishing, plating, metallizing or descaling must be performed, the fineness of details is modified accordingly. But there are no straight-line relationships among any of these factors. Specific problems can be solved only by discussions between product designers and casting houses.

Measurements of Surface Qualities. The standards of measurement of surface qualities in general use have been evolved for application to machined or ground surfaces. They do not take into consideration the possibility that any casting process might produce surfaces comparable in quality with machined ones. The difference is that machining tends to produce regularly repeated or "rhythmically repeated" errors but casting is much *less* likely to have this "wave pattern."

The ordinary technical definitions begin with the basic facts that products have surfaces, that surfaces have contours, and that contours can be divided into special sections for study and that any such arbitrarily selected section is a profile. All of this also is basic to precision investment casting. The definitions then go on to assume that profiles have waviness, a wave being a regularly spaced peak and valley effect, and that wavinesses have roughnesses, a roughness being a sequence of tiny waves upon the larger waves. The waves and their roughnesses form a predominant surface pattern which has a direction in accordance with the marks of the tools which produced it, and the direction of this pattern is called the lay. Any cracks, pits, surprise irregularities, or "irregular irregularities" are called flaws.

It is easy to see why this would be valid for machined, ground or even stamped or forged surfaces since high percentages of irregularities will represent spaces between grinding grits on the final passes of wheels over work, or the vibrational effects of infinitesimal imbalances in various parts of machine tools, or tiny high and low spots on machine slides, or the speed diagrams as press ram pitmans change their pressure angles, or submicrometric off-centerings of pieces in chucks, or other factors which repeat their effects with measurable regularities. The patterns of such surfaces can be photographed and mounted on slides or reproduced on paper, the reproductions can serve as standards of comparison.

Precision investment cast surfaces can be subject to these same patterns, sometimes distressingly so, if made of highly castable alloys. This occurs because the waviness, roughness and lay are machined into the surface of the master pattern or into the surface of the injection mold, and are faithfully repeated as surface details by the casting process.

Aside from reproducing regularities machined into its primary tools, precision investment casting may or may not have regularities of its surface defects. Much depends upon whether or not the investment material is applied by vibrational methods which could produce tiny rhythmic contours in some instances, whether the dispensable patterns as they go through their successive critical range expansions and contractions in being melted out of investments or in solidifying in the molds assume or impose rhythmic surface irregularities, and whether the cooling of cast metals as some areas are changing dimensions in their critical ranges while others still are mushy or highly plastic can induce rhythmic surface irregularities.

So far as is known such possibilities have not been the subject of any scientific research. Until such research has been completed, it is to be assumed that precision investment castings are not subject to regularities of surface defects unless in specific instances observation shows the defects to be regular.

The average deviation from the mean surface, whether root mean square or arithmetical, of a precision investment cast surface may be exactly the same as that of a machined or ground surface. But the as-cast surface is not likely to have the regularities of deviations found in the machined or ground surfaces. And if such regularities are found in as-cast surfaces they are not at all certain to have the same characteristics as in machined or ground surfaces.

For any specific alloy and product, actual surfaces can be supplied by the casting house on sample pieces to be used as standards of judgment or to be placed under the microscope and used as standards of direct measurement. Agreement upon such samples is the preferred practice.

Trade Marks and Identifications. Precision investment casting surfaces can be marked with lettering or with designs to an extent economically impractical for such processes as stamping, forging and machining. The markings can be raised, sunken or both on the same piece. This provides opportunities for adding beauty to designs, for trade-marking, for coding special runs with heat-treatment numbers, for preventing the accidental mixing in stock bins of parts which look very much alike, and for simplifying the assembly and servicing of products in the field.

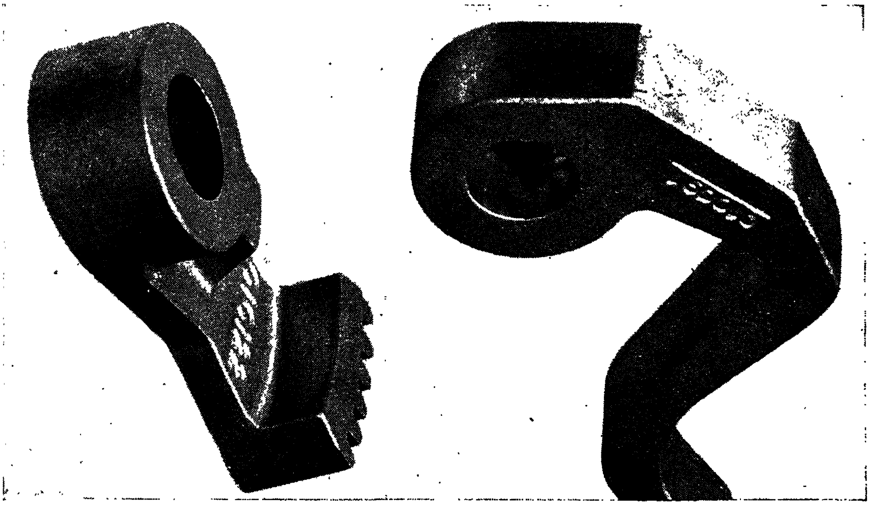


FIGURE 76. Cast-in identification numbers on these SAE 4140 paper machine feeler fingers are neat, clear and permanent.

The cost for raised markings may be slightly greater than for sunken. Much depends upon the positions of the markings in relation to the direction of withdrawal of the dispensable patterns from their molds. If the mold members which apply the markings interfere with this, an inexpensive secondary operation can indent the markings on the dispensable patterns, but a secondary operation to emboss them is more costly.

On heavy sections having large dimensions, the application of raised or bossed patterns has been known to reduce the problems of investment wall spalling with resultant scabbing of the castings. The bosses were helpful because the tendency of the investment to spall is somewhat proportional to the extent of any uncurved and uninterrupted surface. The bosses may be milled off or removed by any inexpensive secondary operation. But in many instances these bosses can be made highly ornamental or functionally useful to the product.

In one of the largest casting plants the operator of the dispensable pattern injecting machine uses a hot stamp to place her identifying code number and the date on each pattern. The customer chooses whether this marking shall be at a place which will be ground off from the casting before shipping or where the identification will remain.

The wax pattern material issued to each operator for a production run is identified in the shop control records. Any divergence from true accuracy of the product caused by misbehavior of the pattern material thus will be shown up by the fact that all of the castings from that run will have similar evidences of pattern material misbehavior. Any errors plainly attributable to misoperation of the injection machine call for improved training of the operator or refined design of the machine. By this means the company improves its techniques.

From the customer's viewpoint, the finding of one faulty casting which bears a given date and code number makes suspect all castings similarly marked. To a worth-while extent the customer then knows which batches to inspect 100 per cent and which can be passed along to the production line after checking only a few. And when one lot proves highly superior to the average, the customer can notify the casting house to check its records of that entire run and sharpen its techniques accordingly.

Chapter 10

The Master Patterns

Unless the molds for injecting or casting the dispensable patterns are to be wholly machined from solid stock or are to be cast and then machined, master patterns are needed for making them. The first law about master patterns is: *No castings can be more accurate than their master patterns.* In fact, most castings are somewhat *less* accurate than their master patterns.

The master pattern is the primary tool of the precision investment casting process. And anyone familiar with toolmaking knows that a primary tool must be designed, and then in most cases must be redesigned or modified in design in accordance with pertinent factors. In all toolmaking, some of those redesigns can be anticipated and some are indicated by the surprise results of experimental production runs.

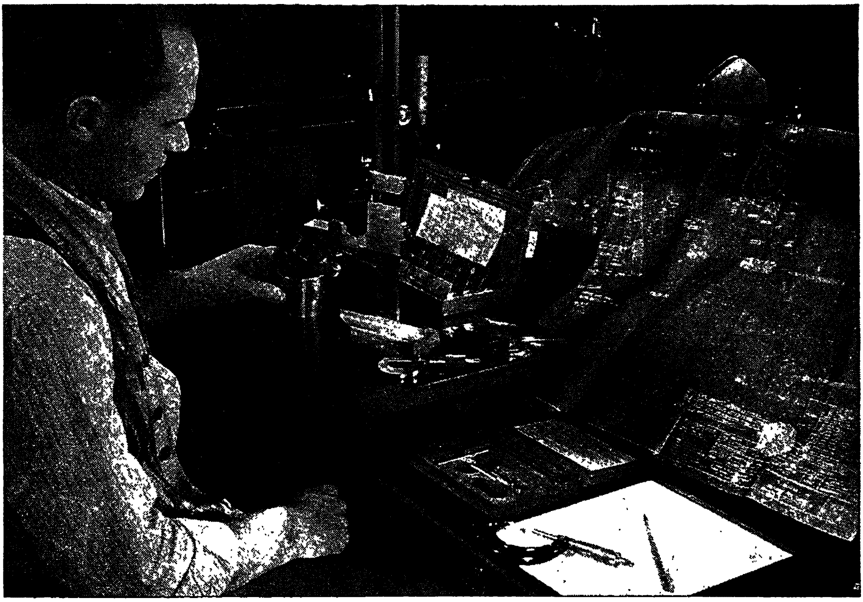


FIGURE 77. The master pattern is a precision tool.

Original Parts Rarely Used. Precision investment casting often takes over the production of a piece which was originally designed for some other process. In rare instances these parts can be used as master patterns. Those instances occur when:

(1) There are no objections to the finished castings being at least 1.5 per cent smaller on all dimensions than the original pieces.

(2) Castings have no directional shrinkage problems for which compensation must be made on the master patterns.

(3) It is economical to make dimensional changes on the dispensable patterns rather than to make master patterns.

(4) Precision investment casting can contribute no improvements to the functional design of the product (see Chapter 5).

(5) The piece is not such that two or more dispensable pattern shapes should be made and then fastened together to make the final patterns, with this operation difficult to perform if the necessary molds are made from this piece as a master pattern.

(6) There are no problems of cores which cannot be solved economically when the piece is the master pattern, and no run-out or other casting troubles.

(7) The piece has no contours which should be machined or otherwise fabricated by secondary operations rather than casting them.

Using the piece as a master pattern sometimes is convenient but rarely is economical.

Rarely a Replica. For the same general reasons as those given for not using the piece itself as a master pattern, the master pattern very seldom is a mere oversized replica of the part to be cast. The costs of trying to make it so can be severe. In one instance a casting house spent $500 to produce such a replica, ran into directional shrinkage troubles, and tried more than 60 different casting pressures and ways of gating the dispensable patterns before giving up and making the master pattern in accordance with the casting problems.

Procurement Problems. The product designer or purchaser can make the master patterns. In fact, some casting houses prefer that their customers do so. But the necessary blueprints should either be supplied or certified by the casting house.

Many casting houses prefer to make their own master patterns, but to bill their customers separately for them. In these instances the "tool ownership" agreements familiar in stamping, screw-machine product, die casting and other processes are signed.

The master patterns useful for one casting house may be useless to another. Nothing in the precision investment casting business is quite so individual as the ways in which the various houses make their dispensable patterns and the mold equipment they need accordingly.

It is *preferred* practice that the casting house and the purchaser agree upon a cost for making master patterns and molds and that all such tools remain the property of the casting house upon termination of the production of the product by that house. This sometimes works a hardship on individual purchasers, but it enables the casting house to apply such tools or parts of tools as it already has in its possession. And in the long run it reduces costs for all purchasers.

Costs of $1,000 for making master patterns are not at all unusual when production runs are to be long, and much higher costs have been known. There almost always is a cost figure large enough so worth-while reductions can be made if the casting house does not have to worry about what tools are its own and what may later have to be shipped to the customer even if of no use to the customer. But, of course, purchasing policies and practicalities must govern each individual situation.

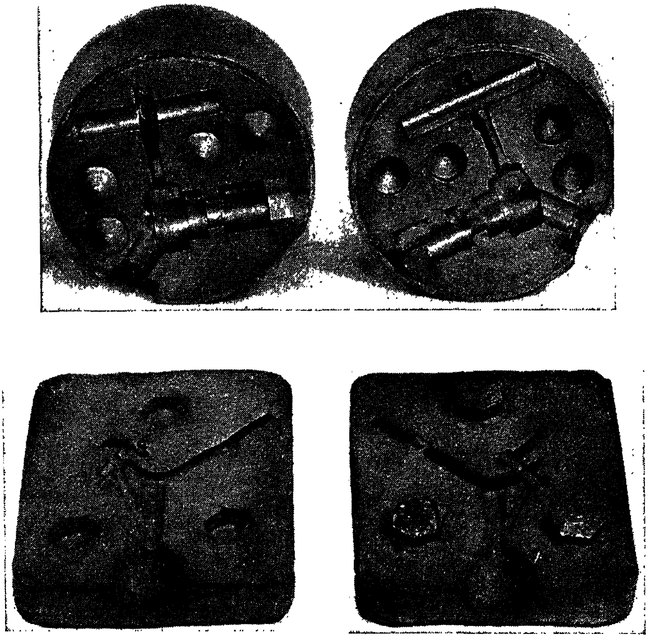
Experimental Net Shrinkage Allowances. As starting figures for schematic or free-hand drawing of master pattern contours, and for no purposes of greater exactness whatever, the net shrinkage on any dimension of the casting as measured from the corresponding dimension of the master pattern may be calculated. Or conversely, a dimension of the master pattern may be calculated by adding a shrinkage factor to the desired dimension of the casting.

For example, 1.5 per cent is the net shrinkage figure most commonly reported to be experienced by the casting houses. If this figure is used, and a 1-inch dimension is wanted on a casting, the corresponding dimension of the master pattern would be 1.015 inches.

All shrinkage tables contain the statement that they are for general application only and that the product designer should consult the foundry for specific information on any casting to be made of any alloy. That statement is emphasized here. The casting house should be consulted before final decision is made about the dimensions of any master pattern.

Differences in Alloys. Every calculation of net shrink has to begin with a "shrink rule" of some kind for the alloy in question. On the basis of *rough averages* for the behaviors of dispensable patterns and of investments, the shrink rules for some of the more common alloys, in terms of inches per inch to be added to the dimensions of the finished casting, would be: gray iron 0.012 inch, aluminum 0.014 inch, bronze 0.012 to 0.022 inch, brass 0.016 inch, steel 0.022 inch, magnesium 0.058 inch. The trouble is, average net shrinks for average alloys are by no means close enough for precision investment casting. These figures serve only to reconfirm the fact that the use of "average 0.015 inch per inch net shrink" for the designing of master patterns is not sufficiently precise, no matter how often that general average may work out in practice. The casting house must specify the correct figure.

Gates, Runners, Risers, Sprues. The master patterns may include gate sections for the patterns. The present trend is toward high precision in designing and positioning the gates. Also, entire sprue and runner assemblies, if so molded, may materially reduce the costs of clustering, especially when two or more dispensable patterns can be simultaneously molded with their gates and runners



(Courtesy Kerr Mfg. Co. Detroit, Mich.)

FIGURE 78. Molds produced by master patterns are intricate.

for clustering in rectangular flasks. Risers, especially blind risers, in rare instances are molded with the dispensable patterns and thus must be included in the master patterns.

Secondary Operations. The whole problem of what contours to cast and what to fabricate by secondary operations must be decided before the master pattern is completed.

In one instance a cored hole was wanted in a position which made clustering difficult. Forty castings could be made per invested flask at a cost of $0.40 each if the hole was cored-in, but eighty could be cast in the same flask at a cost of $0.25 each if the hole was not cored-in. Net cost to drill the hole would be $0.05 per casting, net gain by drilling it $0.10 per casting.

Development Methods for Master Patterns

Master patterns are tools for making tools. They have to be higher in precision than the tools they are going to generate, as is the case with all toolmaking equipment.

The casting house always has its choice of two viewpoints. It can make its master patterns very carefully and simplify the entire casting process. Or it can make its master patterns by "rule of thumb" and make compensations at other steps in the process. Choice between these two, or selection of a compromise viewpoint, depends largely upon the sizes of production runs and the precisions needed.

Careful development almost always is to be preferred. And not the least of the advantages of the development methods suggested here is that they often may lead to the elimination of the master pattern as a necessary tool of casting.

Rubber Mold Experimental. If the product intended to be cast has been made by machining or any other method, it may be suitable for use as a master pattern in an experimental rubber mold. The rubber is preferred for this purpose since it can be kept resilient enough so that if any errors are made in the selection of the parting lines the rubber will pull clear. And the rubber mold need take no longer than 15 minutes to make. For mold-making instructions see page 210.

The pattern material should be injected into this experimental mold and the resultant pattern carefully measured on all dimensions. Several patterns are better than one, but each must be measured independently. These patterns then should be invested and the castings made. Comparing the measurements of the castings with those recorded for the patterns will give accurate shrink data for the castings in question. And from these data the master pattern dimensions may be calculated.

Soft Metal Mold Experimental. If the product intended to be cast has been made of steel or other hard metal, it may be of such contours as to permit being used as a master pattern for making an experimental soft metal mold.

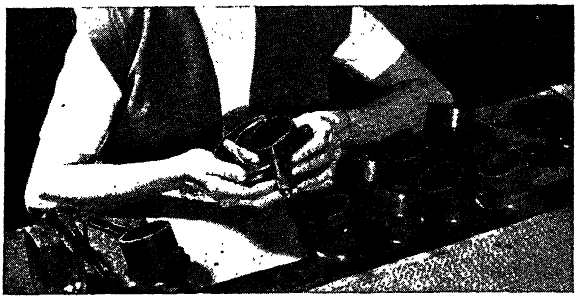


FIGURE 79. Dispensable patterns can be "miked" if the operator has a delicate touch.

The advantage of the soft metal mold over the rubber is that the precision will be higher and each individual pattern will not have to be measured. The disadvantage is that the selection of the parting line must be more accurate.

Dental Stone Experimental. With any reasonably hard, but water-resistant replica of the part to be made a temporary mold may be made of dental stone, plaster of Paris or similar hard setting material. Pattern material may be injected into such a mold, the patterns carefully measured, invested and cast. Shrinkages and other troubles thus may be studied.

This method is quicker than the soft metal mold experimental, but is somewhat less accurate. It lacks the ease and speed of the rubber experimental and does not permit the liberties in making swift judgments of probable parting line positions.

Toolmaking in Wax. This is similar to the method which Benvenuto Cellini used for making fine sculptures. But Cellini did not have modern high melting-point hard waxes. Nor did he have another favorite material, Lucite and the other dispensable types of plastics.

A block of wax or plastic is mounted in a lathe or other machine tool. The lathe is operated by turning the spindle by hand, pulling on the belt by hand if a belt-driven machine is available. Power operation is needed for some of the plastics.

The piece is carved to the dimensions and contours calculated as being necessary for the master pattern. The piece is invested and cast, shrinkages and distortions being measured. Additional pieces then are carved out, embodying the corrections proved to be necessary by the first experiments. The finally developed piece is made oversize, polished down to size, and becomes the master pattern. It should be cast of metal sufficiently durable for master pattern usage.

Die Making in Wax. The "toolmaking in wax" method may be reversed; that is, build mold parts directly of wax or plastics, invest and cast them, machine the castings so that they fit together into a mold. Dispensable patterns may be made by injecting pattern material into this mold, the patterns in turn invested and cast, and the resulting castings measured for shrinkage and observed for run-out and other defects.

This process is repeated, making corrections in the wax or plastic shapes intended to be cast as molds until castings which can be finished into outright molds are produced.

Master Patterns or Outright Molds? It will be seen that by toolmaking in wax and by the other suggested methods a correct master pattern may be developed, and that by die making in wax the mold may be cast to slightly oversized contours and machined down without ever needing a master pattern.

The problem of which to use depends upon whether or not the soft metal mold technique is to be used for the making of final molds, and also upon whether or not rubber is to be so used. Master patterns are necessary for these materials. The economics by which mold materials and methods are selected are very complex, and all of Chapter 11 is devoted to a discussion of this subject.

Die Hobbing in Wax. By the use of a master pattern made of wood or any other hard and smooth material, mold cavities may be hobbed directly into wax. The displaced wax will flow, and must be trimmed with a hot tool to proper mating surfaces. The finished wax pieces then may be invested, cast, and the castings finished into mold parts. The process may be repeated, changing the dimensions and contours of the hob, until castings suitable for making into final molds are obtained.

Toolbuilding in Wax. Several methods have been given by which experimental molds may be made and experimental dispensable patterns produced. Most of these patterns will be too small for the intended castings. And many patterns will be such as to produce warped or otherwise defective castings.

A number of such patterns may be molded. Using a camel's hair brush, a hot spatula, or any other convenient tool, molten low melting-point wax may be painted onto selected areas of these patterns. Paraffin wax often is used for this purpose, since it is of different color than ordinary pattern wax and the progress of the building up may be observed easily.

One pattern should be built up in accordance with dimensional and contoural faults observed in the experimental castings. This one should be measured carefully, then invested and cast, and the results noted. Other patterns should be built up to correct the faults observed in the first one. The end result of the process may be a casting suitable for use as an experimental product, or a casting suitable for finishing into a master pattern.

Die Building with Wax. Die cavities also may be machined or hobbed in wax or machined in plastics, but with cavities larger than desired. The cavity surfaces then may be built up with molten wax, the pieces invested, and mold parts cast.

Alloys in Master Patterns. Master patterns should be corrosion resistant, abrasion resistant, capable of taking high polishes, and low in coefficient of thermal expansion. The alloys most commonly used are Monels, and high-alloy stainless steels.

Master Pattern Surfaces. If a master pattern is to be used for the soft metal mold-making technique, its surface should have the smoothest finish obtainable, otherwise it may be impossible to withdraw the pattern from the soft metal. The lay (characteristic direction of finish roughness) should be as perpendicular to the parting line as can be produced. A "mirror finished" surface with lay parallel to the parting line may refuse to pull out of the soft metal.

Selective Electroplating. In the hands of an electroplater who has the equipment and the "know how," this process deposits metal on selected areas of intricate contours with high accuracies.

Entire master patterns have been built up by selective electroplating, at costs below those which would have obtained by any other process. But more generally selective electroplating is employed for building up undersized master patterns or for bringing to final dimensions and contours master patterns which have deliberately been made undersized so the high accuracies of this process could be employed.

Selective electroplating has solved some difficult problems in which master patterns made in the toolroom were found to be too small on some dimensions or incorrect on some contours. This process also has been highly effective when an original piece formerly mass-produced in a machine shop was to be converted to precision investment casting and the piece itself, by building up its outer contours, could be used as a master pattern hob to sink soft metal molds.

Metallizing. Molten metal spraying can build up an entire master pattern, and very often is the best method. In one instance the estimated cost of machining a master pattern from the solid was over $1,500. Metallizing produced the pattern for less than $500.

As with selective electroplating, much depends upon the house which does the metallizing. The technique requires production of a hydrolized wood base pattern contoured in accordance with the needs of the master pattern. To this a layer of sprayed molten metal from 0.0015 to 0.0025 inch thick is applied. This layer is allowed to cool and shrink, then a similar layer is applied on top of it and is allowed to cool and shrink, and so on until the required thickness is developed. The process is accurate to the extent of plus or minus 0.003 inch. This is not close enough for most master pattern work; therefore the metallized piece commonly is made slightly oversized and machined down to the desired dimensions.

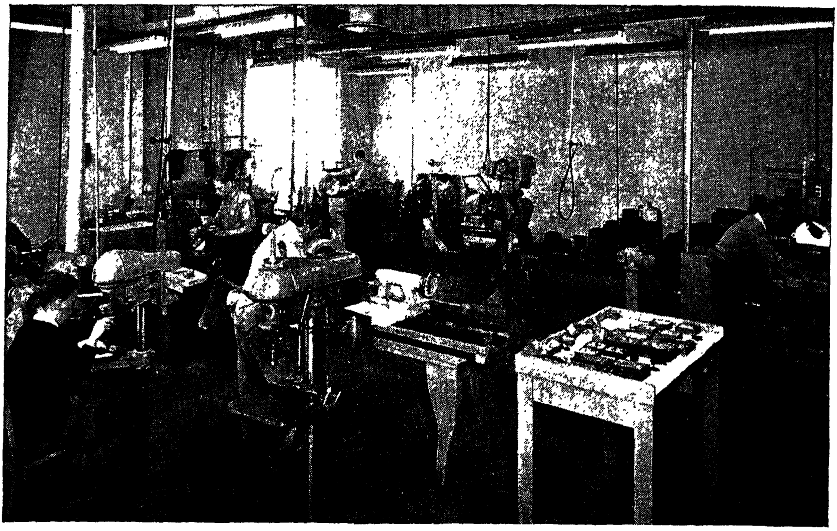
Metallized structures tend to be weak under severe compressive stresses and careful consideration must be given to the alloys of which they are made. But they can be made to stand the stresses of hobbing soft metal molds without trouble.

Undersized master pattern parts can be metallized to full sizes, or to slight oversizes, to be ground down to the desired dimensions. Master pattern parts on which machining mistakes have been made can be salvaged in this way.

Combined Methods. Master patterns can, of course, be machined from the solid by ordinary toolroom methods. Any of the methods suggested here can be used in combination with machining and grinding operations or with each other.

Too often it has been assumed that machining from the solid is the only available method, with the result that master patterns have cost far more than was necessary.

Redevelopment. The importance of having flexible combination methods for making master patterns is not that of reducing their original costs. Very rarely does the precision investment casting industry lose an assignment to make a product really adapted to its techniques because of first costs of master patterns. But as production runs are made, opportunities to improve techniques and reduce costs by redeveloping master patterns and molds are seen. These opportunities must not be lost by high costs to redevelop master patterns or by the fact that toolrooms are too busy to do the work.



(Courtesy Haynes Stellite Co., Kokomo, Ind.)

FIGURE 80. A master pattern- and injection-making department needs the best of toolmaking equipment.

Of even greater importance are chances to improve product designs. Products do not reach their final forms in single efforts. They grow in functional economies as designers discover faults or get new ideas. And when master patterns are easy and inexpensive to make or change, these ideas can be put into effect more easily.

Master Pattern Design. A master pattern is a solid tool about which the material of the mold may be cast under heavy hydraulic pressure, compression extruded, vulcanized, or allowed to set as concrete sets. The master pattern also may be used as a hob.

The master pattern may generate all of the contours of a mold cavity, or only some of them. To be pulled free of the finished cavity it may need separable members. It almost always needs a separable member to generate the area at which dispensable pattern material will enter the mold, the "wax gate."

With all of these options the master pattern is designed first to dimensions and contours which will compensate for the net shrinkage and the net warpage or run out of the castings which are to be made, and second with operating features common to all toolmaking which will enable it to perform its functions.

Design for Rubber Molds. For rubber molds the master pattern can be of any hard material which will withstand the temperatures of vulcanizing. But metal is preferred since it will take part in conducting the heat of vulcanization.

If the mold cavity is to have projecting parts, the master pattern must have cavities or undercuts to generate them. The rubber will pack, or can be packed, into these recesses.

Design for Soft Metal. The soft metal usually cannot be trusted to pack itself into deep undercuts. Therefore separable members of the master pattern must be made, usually of brass or some other metal of sufficiently high coefficient of thermal expansion, so that when pushed with an easy slip fit (clearance 0.001 inch plus or minus 0.0005 inch) into the undercuts and then subjected to the molten temperatures of the soft metals (up to 450 degrees F) the pieces will expand to hold accurately within the undercuts and then will shrink to pull free as the soft metal cools.

These pieces are inserted in the undercuts before the soft metal is pressure-cast about the master patterns. Upon pulling the master patterns from the molds the inserts are to remain anchored in the soft metal and thus are to become the projecting members of the mold cavities. Therefore the pieces must project slightly from the master pattern surface, usually 0.1875 inch or more, in accordance with the wall thickness of the soft metal, in order to be grasped by the soft metal.

Chapter 11

Molds

Molds into which the dispensable pattern materials are injected to make dispensable patterns are as important to the product designer as the master patterns (Chapter 10), and for the same reason. The molds affect the qualities, delivery speeds, and costs of the castings. And the molds are tools for which his company originally or ultimately pays. Terms of payment should be the same as for master patterns. See page 168.

General Types of Molds

The primary function of a mold is to act as a restraining receptacle into which molten wax or other dispensable pattern material may be injected. The restraint must be sufficient to force the pattern material to assume exterior contours which mate with the interior contours of the mold.

Molds can be made of anything which is strong enough to restrain the dispensable pattern material, is not soluble in or adhesive to the material, and is not injured by the molten temperatures of the material. Those temperatures generally range from 125 to 200 degrees F, although in rare cases they are higher.

With these simple requirements, molds have been made of carbonaceous material such as petroleum coke, of hydrolyzed wood, of plastics, of rubber, of soft or fusible metals, of carbon steels, and of alloy steels. In order of commonness of use as reported by several casting houses the materials are:

Carbon steels	At least 50% of all molds
Soft metals	Perhaps 40% of all molds
Rubber	About 6% of all molds
Alloy steels	About 4% of all molds
All others	Negligible, but some may become important, especially some of the reinforced plastics

No attempt has been made here to obtain exact figures but the general picture is correct.

Functioning of the Mold

Simple as the *function* of the mold may be, the *functioning* may be highly complex. It must be remembered that most precision investment castings are of intricate and precision contours. Their contours will be those of the dispensable patterns. High-cost materials and production methods may be needed to produce molds capable of generating those contours. The molds may be required to have intricate as well as accurate parts and moving members.

Complete cycle "floor-to-floor" operation of a mold may be regarded as beginning when the mold is placed in working position, and as ending when the dispensable patterns are ready for the next operation, the clustering one. Two of the steps before clustering, the inspecting of the dispensable patterns and the removing of the pattern material gates if this is done as a separate operation, are not accomplished by the mold. But those steps are so thoroughly affected by the mold that they may be regarded as being within its cycle.

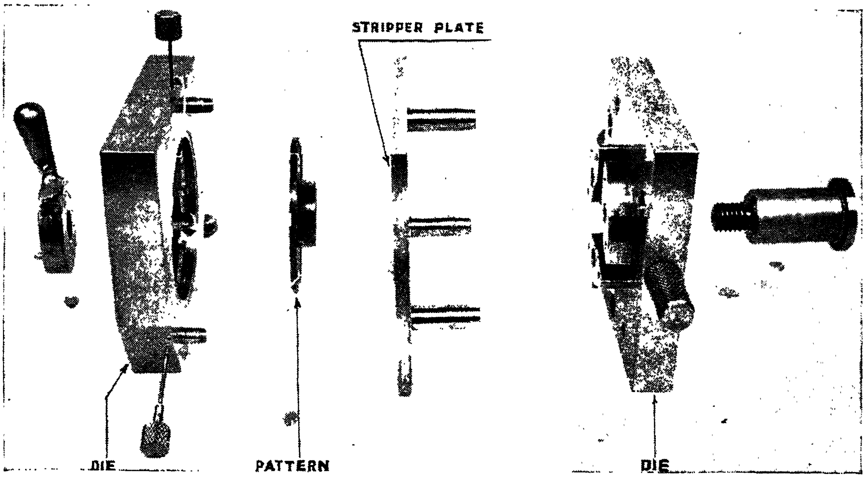


FIGURE 81. Completely separable steel molds permit patterns to be lifted out without distortion, but are slow in floor to floor time.

The cycle given here is a complete one and applies to intricate molds. Not all of its steps are required by all molds. It assumes that the mold is open or disassembled as required to eject a pattern. The cycle is as follows:

(1) Bring mold to working position.
(2) Partly close or assemble its parts.

(3) Insert cores, dispensable pattern material inserts or other parts as needed.
(4) Fully close or assemble.
(5) Bring to pattern material injection machine.
(6) Inject pattern material.
(7) Dwell while pattern material solidifies.
(8) Operate movable members such as core hole punches, thread chasers, which generate contours on the solidified dispensable pattern.
(9) Remove from injection machine.
(10) Set to one side if further solidifying time is needed.
(11) Disassemble or open to remove dispensable pattern.
(12) Operate ejection mechanism if pattern is ejected mechanically. Otherwise, remove pattern.
(13) Set pattern aside to "season" or complete its physical changes of complete solidification.
(14) Inspect patterns.
(15) Cut off dispensable pattern material gate if this is to be done; remove flash.

It is assumed that the operator will have two or more molds, so that he does not have to wait while the pattern solidifies or "sets" in the mold after the mold has been removed from the injection machine [operation (10) of the cycle], if this setting time is necessary.

Normal floor time of operations (1) through (12), as observed in several casting houses, is 2.5 minutes, which works out to 24 molds an hour or about 180 an 8-hour shift, allowing normal time for the operator to be away from the machine during the day.

Fastest time observed was 600 molds per operator per 8-hour shift. This was accomplished on a fully developed, long-run job and with mold-tooling and pattern-injection equipment which came close to being fully automatic.

Slowest time was one mold per operator per day. This mold required 20 successive manipulations of mold members, with pattern material injections and consequent dwell times between them. It was estimated that by breaking the pattern up into separate sections, molding them separately, and assembling the sections into the final pattern, the output could be stepped up to 25 patterns per operator per day. But the purchase contract specified that this assembly method should not be used.

More than one pattern may be produced in each cycle of the mold. The importance of making molds complete and complex enough to do this is made evident by the time taken per cycle. And that time cannot be cut down very much since, especially on thick sections, the dwell time cannot be eliminated.

Mold Temperatures. Nearly all dispensable patterns are wax castings. They sometimes are called "injections." The fact is, pressure applied to the pattern material in its temperature-softened state causes it to conform with the contours imparted by the mold cavities, and solidification caused by loss of temperature causes the material to retain that conformation. This sequence of events defines a casting. Dispensable pattern molds are precision investments for wax castings. And temperatures of the molds are important to the control of precision qualities.

Injecting at room temperature so as to secure a true injection operation rather than a casting one, has been tried, and sometimes is commercially useful. With ordinary pattern wax it required 50 tons of hydraulic pressure. The dwell time [operation (7)] had to be prolonged to almost 60 minutes. The physical effects upon the pattern materials were such that three days of set-aside time were needed before the dispensable patterns became hard enough to handle at the clustering operation.

Mold temperatures are important to dwell time, to set-aside time, and even to directional solidification, when the dispensable patterns are injected as well as when they are cast. And this affects the choice of mold materials.

Molds have been made of aluminum and of copper because the high thermal conduction rates of these metals make the control of mold temperature easier. Any metal mold is, in general, easier to control in temperature than is a rubber one.

One large shop regards mold temperatures as being so important that it places in an infrared-ray-heated cabinet all molds expected to be used in the near future. The cabinet keeps them at constant temperatures of 110 degrees F, as a result of which they are at correct operating temperatures with their very first injectings. Many shops either steam jacket, use electric heaters, or else use cored passages for cooling water, in order to keep their molds at correct operating temperatures while in use.

High-alloy steels which are sluggish in their responses to temperature changes and are low, for metals, in their heat conductivities, sometimes are preferred for molds. If heated to operating temperatures before being put to use, they tend to hold those temperatures and not to pick up much heat from the dispensable pattern materials. This, under some conditions, provides accurate control of the solidification of the patterns within the molds. In their thermal transfer behaviors, these alloys are the exact opposite of the aluminums. Much of the resistance of a high alloy mold to thermal changes depends upon the specific heat of the alloy, and where temperature-sluggish molds are wanted for control purposes, this factor must be obtained from metallurgical handbooks and studied carefully.

Differing Mold Temperatures. As has been pointed out, there are many options of materials and methods for controlling mold temperatures. The options become more complex when different temperatures are needed for high-production injection, dwelling at the injection machine, and dwelling in the mold after removal from the machine. The molds may become the subjects of highly intricate time and motion studies, of balancing of tool costs and speeds against sizes of production runs and selling prices of castings. As was stated in Chapter 1, precision investment casting is not a business for the tyro nor for the undercapitalized shop.

Operation 1. Bring Mold to Working Position. Aluminum or other light metal molds generally cause the least fatigue to the operator. These mold materials often are preferred when molds must be bulky to accommodate cored passages for mold heating and cooling or otherwise must be large. But in many other instances steel molds are lighter on a strength for weight basis and also can be less bulky.

Rubber molds ordinarily withstand rough handling very well, and if damaged by careless or inexperienced operators the rubber molds are quick and inexpensive to replace. Steel molds also will withstand rough handling provided it is not of a kind which will damage their mating parts or working mechanisms or cavity surfaces.

Soft metal molds are vulnerable to rough handling. They often are encased in steel for protection. But the steel cannot cover their cavity surfaces. Light metal molds also are, generally, more subject to damage by rough handling by operators than rubber or steel molds.

Operation 2. Partly Close or Assemble the Parts. Metal molds of any alloys can be equipped with hinges, springs, guides and other common tool and die devices for speed and accuracy in this operation.

Soft metal molds and rubber molds commonly are encased in steel or are fitted with steel sections to which the mechanical operating parts may be attached. But either of these types may be fitted with simple dowel guides and their mating holes without the need for stiffer metal reinforcements. Much depends upon how much force will be exerted by the springs and other mechanical actions and how roughly or rapidly the operator will handle the mold.

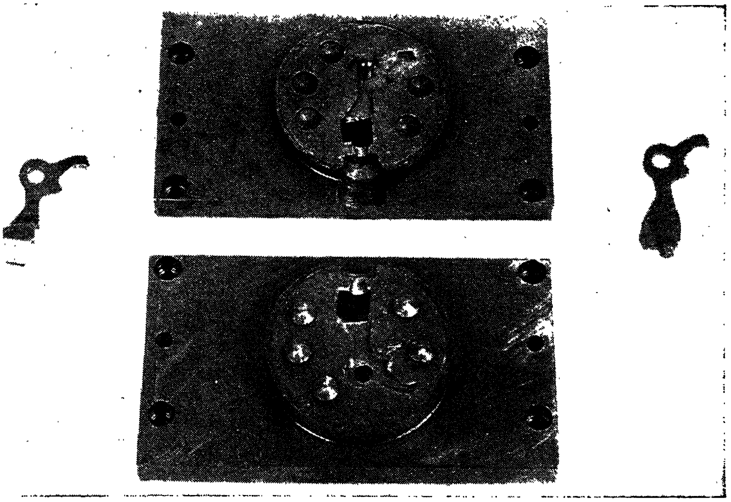


FIGURE 82. Soft metal mold with dowel guides.

Operation 3. Inserts. Pattern inserts may be fragile, or far from fragile. Their positions may need to be controlled with high accuracy, or with little accuracy. They may need to protrude beyond the dispensable pattern, or come flush with its surfaces, or be entirely covered by the pattern material. They may be elastic or resilient.

Fragile inserts may be dispensable patterns of higher melting points than those of the pattern materials about to be injected, but adhesive to those materials. Operating in this way has been known to cut overall master pattern and mold costs by as much as 90 per cent. The premolded sections are molded separately in very simple molds, often are of lower accuracies, higher accuracies, or of either simpler or more complex contours than the main bodies of the dispensable patterns, and commonly are provided with serrated bosses or "tongues" which will protrude into and be gripped by the main bodies of the patterns. In some instances these inserts themselves form the main bodies and the final mold injection does no more than cement them together.

Fragile inserts also may be cores or other sections intended to be readily crushable by the cast metals. When these are for very small holes, or are of thin sections and to be held by one end only, the problems of handling them can be delicate.

Fragile inserts must be held in place by pockets or recesses, by light force fits, or by elastic pressure. Fragile core inserts and non-fragile ones alike may be eliminated by modern multiple coat investing methods. See page 299.

Pockets or recesses for these or any other inserts must either be so positioned that it is practical to reach down into the molds and place the inserts in them, or else must be in molds having movable members which can be closed to fit the pockets over the gripping surfaces of the inserts. In either case metal molds commonly are simplest for providing the pockets, and steel molds usually are most adaptable for this toolmaking problem.

Pockets or other stiff, retaining devices presuppose that there will be clearance between some mating surfaces of the pocket and the insert. It is impossible to make this clearance so fine that the pattern material will not enter it. The "fin" or "flash" thus produced on the dispensable pattern must be cleaned off either from the pattern or from the casting.

Pocket areas may be provided with rubber surfaces if the injection pressure is not to be heavy enough to distort them. This combination mold resource can eliminate the flash problem.

Force fits presuppose high accuracies in the inserts as well as the mold surfaces which mate with the inserts. Force fits therefore are far from being preferred methods for handling fragile inserts. In all too many instances it is impossible to know whether or not the insert has been damaged until the casting has been made.

Resiliencies sufficient to hold the fragile inserts in place can be supplied by the walls of rubber molds, or by spring-actuated mechanisms in any molds. In either case the pressure of the injected investment material must not be sufficient to depress the spring and release the insert. This very often is a problem of the amount of surface area of the actuated member which is presented to the material, force at a given pressure being proportional to the area over which the pressure is exerted. For holding fragile inserts in place rubber molds or rubber inserts often are preferred.

Fragile inserts often are provided with thin wire members which will protrude into mold recesses and hold the inserts in place. These wires remain in the dispensable patterns and their ends engage the investment material walls and hold the cores or other inserts in place against the force of the molten metal during the pouring operation. But in common with any pattern part which is intended to be physically solidified with the investment, these wires have the problem that as the investment material hardens it tends either to shrink or expand, and the wires are held against moving with the investment because they also are embedded in the inserts which are held by the pattern material. The result of the opposed motion often causes fracture of the inserts. The investment wall also may be spalled. Either of these occurrences produces faults in the castings. The protruding wire ends can be nuisances when inspecting and clustering the patterns.

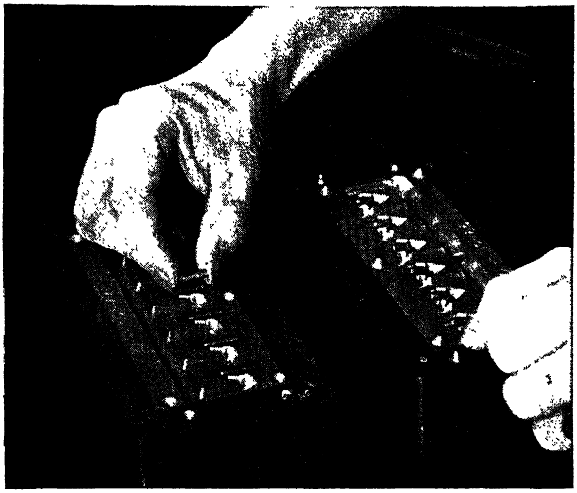


Figure 83. Inserting nonfragile cores.

Nonfragile inserts usually consist of cores which either are to be withdrawn before investing the patterns or else are to remain in the patterns for purposes of obtaining high accuracies by restraining the shrinkages of castings. See page 129. These cores may be held in the molds by the same means as the fragile ones, and they have much the same mold problems.

Nonfragile inserts which are to protrude beyond the patterns must fit closely into recesses of the molds or else the removal of investment materials from the protruding ends must be a secondary operation. Very few need to protrude, and the protruding ends bring the same problems of investment wall spoilage as do protruding wires.

Most core inserts, fragile and non-fragile alike, should come flush with the pattern surfaces. They can be held in that position easily by the elastic walls of rubber molds, by spring actions, or by light press fits. There is little danger of their getting out of place in the ordinary investment. The investment material as it sets tends to shrink slightly inward toward the pattern, and to apply pressure sufficient to hold the core in place during the casting operation. There are investment materials which are subject to "reverse shrinkage" and with these protruding wires may be used in the cores. But several casting houses which use investment materials of mild reverse shrinkage characteristics make their non-fragile core inserts with end bores or recesses deep enough so that the investments will not pull out, then bring the core ends flush with the patterns. (Reverse shrinkage is expansion.)

Resilient cores are made of rubber. They may be integral parts of rubber molds, or separable members of combination metal and rubber molds, or of rubber molds.

Resilient cores are used when a hole which is to follow a tortuous course, or a chamber having an orifice smaller than its main diameter, or any other hole of such shape that it cannot readily be machined, is to be part of the casting design. The core insert is made of the desired size and shape of the hole, the dispensable pattern material is injected, and the end of the insert which protrudes is pulled gently. Under the pulling tension the resilient insert will stretch, become thin, and come out without damaging the pattern.

Inserts may be used in molds of any kind but are easiest to use in molds made wholly or partly of rubber, or in metal molds having rubber members.

Operation 4. Fully Close and Assemble Mold. With rubber molds this can be a simple procedure of putting two or more mold parts together and applying a spring clamp or even putting on a rubber band. With steel molds or with any steel-jacketed molds it can be done in some instances by using spring clamps or quick-acting air clamps or other rapid action mechanisms.

Some molds are intricate assemblies of parts and can be assembled rapidly only after extensive motion studies have shown just how the operator should use his hands and fingers. Wing nuts and all other kinds of rapid fastening mechanisms are used.

Clamping pressures or fastening rigidities must be superior to the forces imposed by injection. To some degree, the type of mold material possible to use is controlled by the injection pressure. Rubber molds, especially if not steel encased, will not stand more than moderate injection pressures.

Soft metal molds tend to be marred or peened by rapid handling at this step. Therefore they often are encased in steel jackets which are fitted so carefully that steel mates with steel and steel takes the wear. This may leave slight crevices between the soft metal inner sections. The mold material can enter these crevices and produce fins or flash which must be removed as a secondary operation. To eliminate this operation all-steel molds often are preferred.

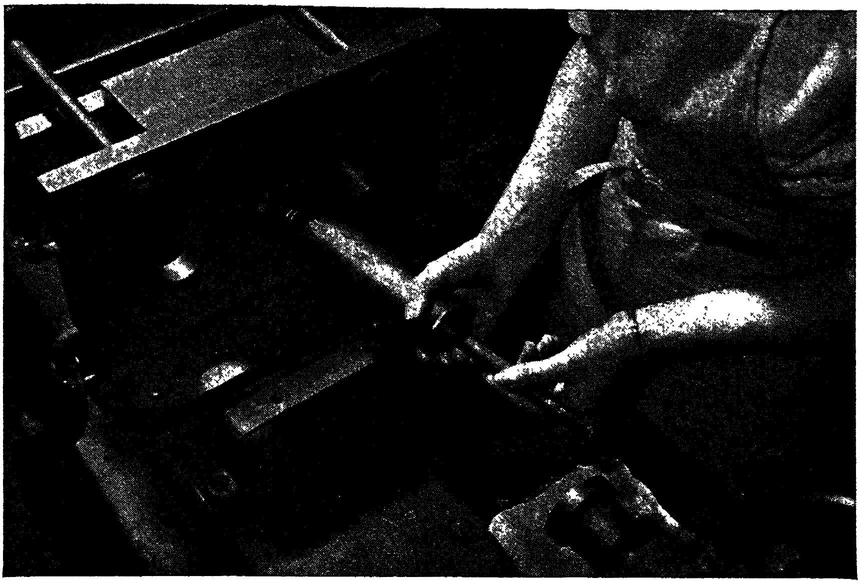


FIGURE 84. Injecting with plunger gun which will be operated by hydraulic pressure. The clamps must hold the pressure.

Steel-encased rubber molds sometimes have this same flash trouble. The rubber inner sections can be made thicker so that they extend slightly, perhaps 0.005 inch, beyond the edges of the steel casings, and when the molds are closed rubber meets rubber and compresses until steel meets steel, thus closing the crevices. But the problems of reducing the visibilities of parting lines always are greater with softer than with harder mold cavity materials.

Operation 5. Bring Mold to Injection Machine. This operation may be in reverse. The mold may be stationary, clamped in a fixture and perhaps with steam or water pipes all connected for heating or cooling, and the nozzle of the injecting machine be brought to the mold. Steel commonly is preferred for fixed position molds, although either soft metal or rubber may be used for some of their interior parts.

Contact between mold and nozzle must be accurate enough, and pressure heavy enough, to hold the pressure of injection. Contact accuracy is not difficult to provide in any mold material. But ability to hold the pressure sometimes is enough of a problem so that no matter what the remainder of the mold is made of, the orifice is of steel, perhaps with a rubber or other replaceable slightly resilient contact member to improve the fit and reduce the maintenance costs of wear.

Mold Lubricants. At some part of the cycle of closing the mold, and before injecting the dispensable pattern material, a lubricant may be injected into the mold cavities. The purpose is to break the surface tension of the pattern material. The material as it enters has friction with the mold walls. The friction tends to cause the material to roll or warp. This process may entrap air beneath the surfaces of the patterns, the air appearing as "skin bubbles." The bubbles cause rejections of patterns, and if undetected, may cause faults in the castings.

Lubricants may be oils, glycerin, alcohol, aerosol, silicones, soap mixtures or powders. Injection usually is by air spray, often with a hand syringe.

Need for this operation appears to decrease with increases of injection pressures; therefore the lubricants most often are used with rubber molds. When performed, the lubrication operation introduces a cycle complexity which sometimes leads to adoption of metal molds and injection pressures which avoid the need for reducing the surface tension of the pattern material.

Operation 6. Inject Pattern Material. The pattern material may be at various degrees of liquidity ranging from wholly liquid to semi-liquid to wholly plastic. In any instance it is subject to all the laws of hydrodynamics.

For information about hydrodynamics the reader is referred to the literature on the subject. But in simplicity:

(1) The force or current of a fluid tends to travel in a straight line unless deflected.

(2) There is friction between the entering pattern material and the walls of the mold.

(3) That friction plus the interference of any projecting contours of the mold, or any need of the current to turn a corner, tends to set up

eddy currents having directions different from that of the original current.

(4) The original current will be altered by the eddy currents up to an area in which its force and viscosity permit it to cut through them by viscous shear.

(5) As the original current reaches the end of the mold or some other major obstruction it will double back upon itself and form reverse or otherwise deflected currents having forces and eddies and viscous shears of their own.

(6) Some of the forces of the original current will be expansive and will cause a widening of the original current as it enters the mold cavities. The widening will be oblique to the main current, weaker in viscous force, and first to strike many surfaces and set up eddy currents.

(7) The original effect will be one of some uninterrupted forces but many diverse turbulences.

(8) As the currents double back upon themselves and quiet down the forces will become wholly expansive, especially since the injector will continue its pressure. The material then will move outward from its original path, fill up all crevices, and in so doing create many small currents with effects similar to the original one.

(9) The material in the filled mold will approach a state of rest.

(10) Any mold chamber member capable of being resiliently deflected by the currents, and then of springing back when the pressures become equal on all sides of it, may complicate the currents but is not likely to reduce the effectiveness of the mold filling operation.

From this picture of an injecting operation several propositions, not as yet confirmed by special scientific research in the precision investment casting field, may be deduced.

(11) The forces of the entering material are not instantaneously equal in all directions but are much heavier in some directions than in others. And as those directions conflict a great deal of shear can be imposed upon anything which resists them. This is why fragile inserts in some locations in molds are fractured while in other locations they will stand up.

(12) The scrubbing action on mold surfaces will be proportional to such factors as the viscosities of the materials transversing them, the velocities of the currents in contact with them, and the pressures against them. This scrubbing action is why, in molds of some designs, soft metals last for only 500 injections before needing maintenance while in others they withstand 5,000 injections at the same temperatures and pressures of the same pattern materials.

(13) The lower the mold temperature, if it is lower than that of the material, the greater the viscosity at the surface contact and the more abrasive the scrubbing action.

(14) The higher the coefficient of friction between mold and material the more severe the scrubbing action.

(15) Progressive solidification cannot begin at any surface and progress from there while that surface is being scrubbed. Rather, the solidification will begin where the material first comes to rest. This explains some of the accuracy effects of progressive deposition, the accuracy generally being greatest where solidification first occurs.

(16) Solidification can occur first at such areas as to block the feeding of the material to other areas.

(17) As the material progressively solidifies, residual stresses of cooling are set up in it. These are accompanied by other residual stresses caused by the increasing viscosity of cooling, this viscosity acting to inhibit the attempts of the material to continue flowing. Need to release these stresses explains the need to let the patterns set or season both within and after leaving the molds. These stresses also can cause patterns to warp or run out, to swell and sometimes to shrink.

(18) The entire picture is complicated by the need of the air to escape as the material enters.

(19) When the materials are at a comparative state of rest but still are under pressure, their forces are greatest in total effects for equal areas on flat surfaces and less on curved ones. For this "forces upon flat surfaces *vs* on curved ones" effect the reader is referred to any standard book on pressure vessels.

(20) The original forces and final forces may be greatest on the same surfaces or upon different surfaces. But the final forces will not be the same on all surfaces unless the mold chamber has the contours of a perfect sphere.

The picture is one of varying forces, solidifications, stresses, strains, deflections, and erosivenesses.

Steel has the brute stiffness and strength to withstand all of this with greater certainty and less experimental work to find out how to overcome unexplained effects than has any other material commonly used for molds. But other mold materials, by their very resiliencies, can handle some conditions better than steel.

Pressure can fracture. Aside from this, high viscosity is the factor most likely to contribute to mold damage. High viscosity is used because it accompanies low temperature of pattern material and the lower the temperature the less the range over which the material must cool and therefore the less the contraction from shrink and the higher the overall accuracy, coefficients of thermal expansion being nearly equal for the various pattern materials in common use. The higher the viscosity the greater the pressure needed to force the material to fill out the mold. That is why pressure and viscosity usually accompany each other where high accuracy is required. Steel therefore is likely to be the preferred mold material for high accuracy dispensable patterns which result in high precision castings.

Because of the peening effect, some of the houses most thoroughly experienced with soft metal never use it in molds which are to be injected at pressures of over 1,000 psi.

Operation 7. Dwell While Pattern Solidifies. This dwell may be required to endure for any period from a few seconds to several minutes. It has two functions. The first is to continue feeding the pattern material to fill up voids caused by shrinkage, as a riser feeds a casting. The second is to provide seasoning time before the pressure is released. The pressure can continue to the extent that the cooled material is plastic.

Water cooling of molds can speed the solidification of the material and decrease this dwell time, thus conserving the time of the injection equipment and of the mold. Any kind of mold material can be cored, drilled or otherwise be given passages for the cooling water. But if air cooling is to be used, a mold material high in heat conduction may be preferred.

Rubber molds usually expand under the pressures of injection. During the dwell time they will contract unless the continued pressures prevent this. Expansion and contraction tend to be greatest in the directions of greatest effective pressures and of least resistances. The effective pressures are dependent upon cavity contours, pressures being most effective against flat contours. The contours are established by the designs of the castings to be made. But the exterior contours determine resistances to expansion, and the exteriors can be controlled by the needs of the mold. Therefore the directions and amounts of expansion and contraction are subject to control in the mold design.

This contraction or "following the pattern down" affects the pattern contours in ways which metal or other rigid molds cannot duplicate. It is one of the reasons why rubber molds can produce fidelities to intricate contours which cannot be attained in molds of any other materials. It also solves many problems of selective area accuracies. The mold areas desired to be highly accurate are made of steel or other hard material, and are cooled so they solidify first. The mold areas which can be of less or even of "random" accuracies are made of carefully designed rubber sections so that they can contract and force the pattern material toward the steel areas during the dwell period.

When dwell time is long, injection machines may be equipped with compressed air connections. The pattern is injected, the air hose attached at the wax gate, the air pressure applied, and the mold moved to one side with the pressure still in operation. A second mold then is positioned at the nozzle, the injection mechanism started, and the air pressure disconnected from the first. This avoids wastage of the time of the machine during a protracted dwell period.

FIGURE 85. Hydraulic injection permits high viscosity with low velocity.

Operation 8. Operate Movable Members. At some point near the close of the dwell period movable die members may be operated to perform machining operations on the dispensable patterns. Holes may be punched instead of using core sections in the dies to produce them. Threads may be chased. If two or more patterns have been molded at a single injection and it is not desired to cast them in the same flasks, knives may advance to separate them. Cutters may advance to shear off flash and to eliminate almost entirely the visibility of exterior parting lines on the castings. At the end of the dwell, pressure may be cut off from the injector and the wax gate severed.

The advantage of performing these operations at this time is that the patterns are held in the mold as in a perfectly fitted vise or fixture. At no time subsequent to removal from the mold can the patterns be quite so perfectly fixtured for such operations.

Power for actuating the mechanisms may be manual, electric motor, pneumatic or hydraulic. The advantage of manual manipulation of movable parts is that the complication of power devices either permanently attached to the mold or separately attachable to it is avoided. The advantages of power are those of speed which conserves the time of the equipment, and those of automatic precision accuracy of control. Very rarely is the power requirement any greater than an operator can easily apply with his fingers.

Where such operable members are to exist, steel is the mold material in which they may most easily be applied. Soft metal usually must have steel jacketing of thickness adequate for all bearings and all stiffnesses of support and correctness of alignment for these parts. Rubber almost always must have such steel or other solid metal jacketing.

Operation 9. Remove from Injection Machine. This may be a simple matter of pulling the mold away from the nozzle or the nozzle away from the mold. But it sometimes requires the releasing of clamps or fixtures, or the braking of a centrifugal injecting machine so that it comes to a stop.

When the mold is in fixed position and is not moved from its supports for any operation, a turntable, pivot, or travelling ways may be needed in order that the injection machine may be moved to a second mold while the first one is going through its unloading and reassembling cycle.

In the absence of mechanical equipment, or in the presence of cluttered work benches, a great deal of time can be wasted at this operation. This does not affect the selection of mold materials, but it has a direct bearing on the equipment costs for economical molding.

The costs of handling are related to bulks and weights of materials. See operation 1, page 182.

Operation 10. Set Aside for Further Solidifying Time. The ability to conduct heat, and the specific heat of the mold material, affect this operation. In one example, two rubber molds of a single pattern were needed by each operator at starting time in the morning. One mold was emptied, reassembled and injected, while the other was set aside for cooling. By noontime four molds were needed so that three could be set aside to cool and used in rotation. By midafternoon, especially on hot days, six molds were needed.

This did not affect mold costs very much. Rubber molds are quite inexpensive. But when the same thing has to be done with complex metal molds, the cost factor is more serious. For example, heavy and cumbersome steel molds were needed for a comparatively small run of highly intricate patterns. The set-aside time was great enough so that considerable time of injection equipment would be wasted unless two molds could be cooling while one was in use. The cost to make each mold was $2,000, the cost for three would be $6,000. By using Dry Ice to cool the molds it was found practical to make only two. Thus by adding slightly to the cost of set-aside time the mold cost was reduced by $2,000.

Set-aside time can be made useful for operating movable members as described under operation 8. The choice between dwell time and set-aside time for this depends upon whether the condition of the pattern material is suitable at dwell time, and upon which point in the production cycle offers the most mold time which otherwise would be wasted.

During set-aside time, solid core parts may be withdrawn if made removable or withdrawable, and so may resilient cores. In many instances the mold problems of fragile inserts may be solved by coring-in the spaces for them with solid metal mold members, withdrawing those members and replacing them with the fragile inserts, during set-aside time. The advantages of performing these operations at this time are those of conserving the production time of the molds and of having the patterns held in a perfect fixture while the operations are performed.

As pressures and viscosities of pattern material injections become higher (see operation 6) the set-aside time may need to be increased. Pattern materials go through critical ranges as they "set." Within those ranges they remain too soft to handle without distortion, or become too sticky to handle, or swell and shrink and otherwise change their dimensions and contours. Until those processes are well advanced, the patterns either cannot be taken from the molds or else should not be removed from the dimensional restraints of the mold members. The time duration required by the setting is directly affected by the pressure and viscosity of injection. The higher the pressure and viscosity, the longer the setting time, although much depends upon the composition of the pattern material and the thicknesses and contours of the pattern sections.

The tensile strength of the pattern material is inversely related to its temperature. As the material becomes hotter it tends to become weaker. Therefore the pattern sections which cool first and cool most tend to maintain their dimensions and accuracies and to impose shrink distortions upon the more slowly cooling sections. But since most pattern materials are plastic at room temperatures, if light sections cool first, the heavy sections as they cool may accumulate sufficient force (total tensile strength being proportional to thickness of section) to distort the light sections, with the result that both are distorted.

Advantage can be taken of this to cool some sections more rapidly than others and secure selective area accuracy. This is an important factor in precision investment casting design. The highest accuracies of this process should be held only on selected areas.

The reverse procedure may be followed, and selective areas of molds be kept at higher temperatures to counterbalance the tendencies of shrink forces to cause distortion. Or the entire mold may be cooled by slow gradients which inhibit any area of the pattern from cooling and shrinking more rapidly than any other.

It is during this setting period that the abilities of rubber to expand with the injection forces and then contract with the pattern, to "follow the pattern down," become most valuable. The metal sections of combination molds are cooled for high accuracies of those pattern areas, while the areas within the rubber sections are either kept warm by the insulating effect of the rubber or are specially warmed. The rubber keeps pressure on its areas and forces their contours to remain in conformation with its mold surfaces even though it may not preserve as high accuracies as are obtained at the metal molded areas.

Molds often are made of Catalin or similar plastics having comparatively low thermal conductance. Since these plastics themselves are molded, large numbers of pattern mold cavities may be had at low cost. The molds are injected and are set aside, sometimes for hours. Dispensable patterns of the very smoothest surface textures can be obtained in this way.

Special heating and cooling provisions may be applied to any mold materials but generally are easier to produce in steel than in any other molds. In fact, the great majority of setting-time problems are most easily solved by steel molds, or by molds which include steel jacketings and other parts.

Operation 11. Disassemble or Open Mold. This is similar in its problems to operations 2, 3 and 4. But there is one important difference. Those operations must be performable without injuring molds or inserts. The disassembly also must be free of injuries to the patterns.

It might be possible to do some machining of the pattern by the motions of mold parts during disassembly or opening of the molds. But in most instances the members which engage the pattern in such manner as to interfere with its ejection must move straight out, or must be so controlled in motion as not to injure the pattern.

The use of flexible core and other pattern parts which will stretch thin and pull out often is an aid to disassembly. The slight flexibilities of rubber mold parts or of spring-actuated members also can be helpful, especially if fragile inserts are within the patterns. Fragile inserts can be injured at this operation without their injuries being discovered until they show up as faults in castings.

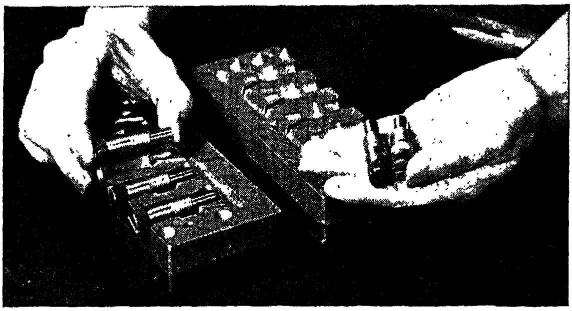


FIGURE 86. Inserts generate female threads, then as they are twisted to back them out, smoothly chase the threads within the patterns.

Most of the disassembly problems require positively guided sliding motions of the mold members, or positive radius revolving motions, or other accurate mechanical motions which are most easily obtainable in steel mold parts, or in steel jacket and sectional parts for soft metal and for rubber molds.

These disassembly mechanisms are not necessarily built into the mold itself. Very often they are separate mechanisms mounted or kept at the place where the mold spends its set-aside time. When this is so, a great many of the disassembly advantages of steel molds are cancelled and the toolmaker becomes more free in his choice of mold materials.

Operation 12. Ejecting the Pattern. In the great majority of molds the pattern may be grasped by the wax gate and lifted out. This may be done with tweezers or even with the fingers.

When the pattern is in a deep recess, removal without injury may require sliding it along the mold walls for the full distance of its width or height or even its length. If a very slight pattern draft is permissible to the product design, the first short movement of the pattern frees it from the mold and permits it to be lifted or dropped out. If there can be no pattern draft, an ejection mechanism may be needed to push the pattern out.

The ejection mechanism may be built into the mold, in which case steel molds or steel jacketings on other molds facilitate its design. The ejection mechanism may be part of the equipment at the set-aside time station, thus simplifying the design and operation of the mold itself and offering more options as to mold materials.

Flexibilities of rubber molds or of rubber parts in other molds can simplify ejection problems. There are instances in which a pattern may be ejected from a rubber mold by grasping the sides of the mold with the thumbs and pressing the fingertips against the outer surface of the mold, whereas in any metal mold a somewhat complex mechanism would be needed to move the pattern without marring its surface.

Ejection mechanisms may be actuated by manual force, by mechanical motions which apply leverages, by compressed air, by electrical devices, or by hydraulic force. The power needed is not great. Powered mechanisms are more subject to automatic control and thus can prevent human errors which might injure patterns.

Operations 13 and 14. Season and Inspect. The patterns continue to release residual stresses and change physically after being ejected. They need to be allowed to season. The seasoning time can range from a few minutes to several days, depending upon the pattern material, the relative thicknesses of sections, the thicknesses of the heaviest sections, and the injection pressures. Generally, the higher the injection pressure, the more abrupt the juncture of a thin section with a thick one, or the thicker the heaviest sections, the longer the seasoning time.

During seasoning time, sections may tend to warp or run out. The mold cavities therefore may be made of such false contours that the effects of warpage will be to bring the patterns to their true desired contours and accuracies. See page 136.

Seasoning usually is done in open trays. Most of the trays have flat bottoms. But in rare cases the patterns are so soft that the tray bottoms must be chambered to support their contours lest the weights of the patterns cause various sections to deform. When

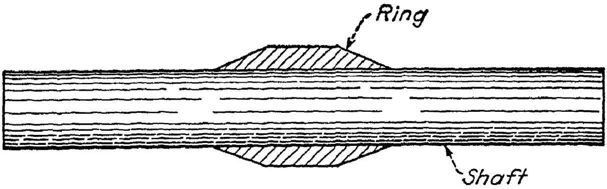


FIGURE 87. Rubber insert for internal relief undercut.

1. A smooth steel shaft of the size and shape of the desired orifices is made. Orifices are shown the same size but may be of two different sizes if desired.
2. A rubber ring member having inner contours to fit the shaft and outer ones as desired for the under cut is assembled on the shaft. There may be more than one ring for multiple under cuts.
3. This assembly is used as a mold insert.
4. When the pattern has cooled and solidified the steel shaft is pulled straight out, leaving the ring within the pattern. Tweezers or any other suitable tool then can grasp the ring, collapse it inward, and pull it out.

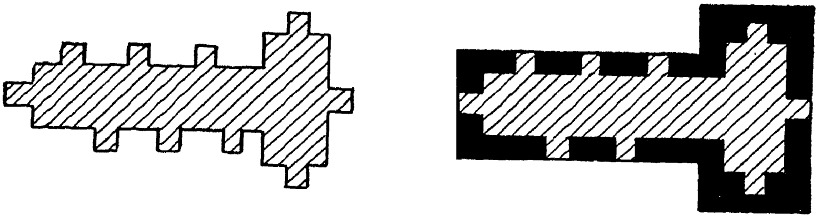

Core pattern — Core pattern plus enrobing wax

FIGURE 88. Enrobing technique to correct heavy section warpage.

1. A pattern somewhat smaller than the desired one is molded. This may be solid or hollow. It has either lands or bosses which protrude to contact the walls of the final mold. They must be so contoured that the enrobing wax can pass and surround them. This pattern requires only very low accuracy, is best made in a low cost rubber mold, and of reclaimed pattern material.
2. The pattern is set aside to season, warp, "belly" as it will.
3. This pattern is placed as an insert in the final mold and high grade pattern material injected or "enrobed" around it. Since the main body of pattern material is seasoned it will hold the thin contour coat against warpage and thus can preserve precision dimensions and contours on large patterns.

seasoned, of course, the patterns are hard and rigid enough to be handled for further operations.

Anything from casual to strict inspection may be made before the patterns are seasoned or while they are seasoning. Casual inspection often will serve to discard any obviously faulty ones and make sure that enough good ones have been produced for the immediate production run. But strict inspection may be needed if the patterns are of sensitive or critical types in which the slightest misbehavior of the pattern material may call for changing of injection pressures or of other factors in the mold operation.

Most of pattern inspection is done after the seasoning is completed. Inspection usually is visual, the patterns being laid against ground glass or any other screens upon which their proper contours can be laid out, and then viewed through illuminated magnifying glasses. But any inspection tool which will not mar the patterns may be used. Dial gages with broad contact surfaces are useful for close tolerance inspecting. The inspection machines which magnify dimensions, and then reflect them upon screens where they may be compared to standards, are highly effective for critical contours.

Mold materials and designs directly affect inspection costs and practices. It often is economical to spend less money on the molds, inspect the patterns more thoroughly and reject more of them. But in other instances the costs to inspect critical contours can be so high that superior economy lies in the making of better molds and reducing the need for inspection.

Operation 15. Cutting Off. Up to this point the pattern material gate may serve as a convenient section for grasping the pattern without injuring it. But if the gate is not of the correct position and contours for casting, it should be removed. It may be cut away with a simple die that will generate the desired contours on the pattern, provided that the contours are such at the gate area that this is practical. It may be cut off with a hot tool, but never without leaving a telltale mark on the pattern which will be reproduced on the casting.

If the casting is to be machined at this area, or for some other reason the marks are not of critical importance, there is no problem. But in a great many instances the mold should be so designed that the pattern material gate will be cut off by a movable part during one of the dwell periods, or will be at a noncritical surface. This may affect the whole problem of the viscosities and pressures needed for filling out the mold, the materials of which the mold is to be made, and the mold costs.

Removal of flash often may be done with the fingers. But if elimination of the parting line is highly desirable, flash removal can be a problem similar to that of the wax gate, and more complex in the areas, continuities and contours involved.

The last word on mold design has not been said until the pattern is cleaned of all flash and ready for clustering.

The Set-Aside Station. Operations 10 through 15 may be performed at tables where operators open molds, take out patterns, pass the molds back to the machines for refilling, and put the patterns into trays for seasoning, inspection and flash removal.

The set-aside time may be so brief that the operator opens each mold immediately after injecting it, ejects the pattern, inspects it casually to make sure that his injection machine is functioning properly, and then puts the pattern into a seasoning tray.

In either of these methods, if the pattern is of complex contours and critical accuracies, or there are inserts difficult to handle, or there are manipulatable members of the mold which must be actuated after the injection, then the mold must be of complex design and made of materials which are capable of high accuracies and are durable in their precisions.

The set-aside station may also be a turntable, a slowly moving belt, or a flat table with a series of mechanical devices. Here an operator, or a series of operators, may connect cooling or warming devices, manipulate movable members of molds, apply mechanical devices to disassemble the molds and eject the patterns, inspect the patterns and place them in contoured seasoning trays. With mechanized set-aside stations the molds can be returned to the injection machine operators in partly closed positions, with inserts in place, or even in fully closed positions. The inserts often are placed by mechanical means to eliminate human errors or to do the work more rapidly than is possible by using hands alone.

There are plenty of patterns for which no intricate equipments are needed either in the molds or at the set-aside stations. But where operations are intricate they may be confined to the molds, in which case the primary mold material must be steel or else steel jackets and sections must be fitted to soft metal or rubber molds. Or large numbers of the operations may be performed at the set-aside station, in which case the options as to mold materials are much wider.

This is the usual problem of the tool designer in any field whatever: whether to concentrate his intricate operations or separate them.

Once a mechanized set-aside station is established, the mold practices of the casting house usually are selected to fit it. This also varies the selection of mold materials.

Costs of Molds

There is no straight-line relationship between mold costs and mold materials.

Molds are tools. Their costs are subject to tool economics. The principal factors of tool economics are:

(1) Experimental costs. Tools do not always work correctly in their first designs.
(2) Preparational costs; costs of tools to make tools.
(3) Tools materials costs.
(4) Toolroom machine and labor costs.
(5) Tool maintenance costs.
(6) Recoverable value of tool materials after tools are worn out or obsoleted.

Experimental costs are nearly all in favor of rubber molds. A rubber experimental mold to find shrinkages and the like often can be made with $1.00 worth of materials and 15 minutes of labor. Soft metal molds are second in this respect, steel molds generally very poor.

Preparational costs are in favor of steel. Rubber molds need master patterns of sufficient accuracies, soft metal molds generally need strength as well as accuracy in the master patterns. Soft metal molds can, of course, be machined like hard metal ones, but this practice is rare.

Tools materials costs generally are in favor of steel. But the materials costs for molds rarely are important items in total costs.

Toolroom machine and labor costs are generally, but not always, in favor of rubber first, soft metal second, and steel last. In fact the economics of molds costs is largely that of determining when the high toolroom costs of steel overcome the advantages of steel.

In an instance of a fairly simple pattern, rubber molds cost $4.00 each, but since six would be needed to provide enough set-aside time per mold, the net cost would be $24.00. If two soft metal molds were needed, the net cost would be $35.00. Two steel molds would cost $70.00. But in hundreds of other examples the figures would be altogether different. In one instance only 60 highly intricate castings were wanted. Toolroom time to make the steel mold was 24 hours, which at only $5.00 an hour for one man and the machines he used, would be $120.00. Yet steel molds proved to be the least costly to make.

Maintenance costs are in favor of steel, if production lots are large enough to cause maintenance troubles for any molds. When rubber molds need maintenance it usually is least costly to discard them and make new ones. Either soft metal or steel molds can be made to the lowest dimensional limits permissible for the patterns and then be allowed to wear until the patterns approach the upper dimensional limits, after which the mold cavities can be resurfaced at the worn areas and the procedure repeated. Steel molds commonly wear much longer than soft metal before needing such attention, and the costs to resurface them are not necessarily any higher.

Under heavy injection pressures, soft metal mold cavities may creep or deform rather than wear. The metal is still at the cavity but has become displaced. It often can be replaced by forcing the master pattern back into the mold cavity, using hydraulic pressure of at least 10 tons.

Recoverable value of tool materials is in favor of soft metals. Soft metals can be remelted, even remolded or rehobbed. Rubber seldom is recoverable to any important extent. Steel is scrap when obsoleted unless another mold similar but larger in cavity contours is wanted. But the guides, slides and parts other than the mold cavity areas of steel molds often are highly recoverable.

Molds usually are designated by their cavity materials, since the cavities are likely to be the most costly contours to obtain. Thus a mold having soft metal cavity areas but a steel jacket or frame is a soft metal mold, and a steel-jacketed rubber mold is a rubber mold. When cavities are of two or more materials the molds are combination types.

Jackets may be of brass, aluminum or other hard metals as well as steel. In some instances jackets are rubber over hard metal, the purpose being to prevent marring of surfaces which the mold may strike in handling or to make the mold less dangerous to the hands of the operator. Hard metal jackets are highly recoverable for use with other molds.

In terms of broad generalities, but allowing for a great many specific exceptions and for wide areas of overlap, the division of the fields among mold materials is about like this:

(1) For high fidelity reproduction of contours and of surface details, rubber is preferred. Also for experimental runs and for small lots.

(2) For special conditions requiring critical control of temperatures, aluminum, tool steel, brass and other materials may be preferred. Rubber also has applications to special conditions.

(3) For the great majority of medium runs, soft metal is preferred, with or without steel jacketing.

(4) For long runs and for many conditions no matter how long the run, steel is preferred.

Mold Materials vs Problems

The average casting house has its favorite kinds of mold materials, knows how to use them, and prefers to avoid experiments and to get on with the business of making castings. There are all sorts of ways of solving specific problems. The materials preferred by a house may lend themselves to the mechanical equipment of that house, be familiar to its labor, have other economically valid reasons for being applied to all tasks.

With those reservations in mind it is practical to list the most common mold problems and the mold materials most likely to solve them. But this list is for checking and suggesting purposes only. It is a starting point. When the mold designer faces a combination of problems he must apply his own weights to the various factors, as shown in the table on pages 204 and 205.

Mold-Making Methods

The cost and type of mold affect the functional values which the product designer can obtain in a precision investment cast product. The economics which govern sizes of production runs are affected, and so are the kinds and values of alloys which may be cast and the costs and types of secondary operations which must be performed in the product designer's shop. Understanding between the product designer and the casting house is needed.

The first step in the making of a mold is to blow the product design up so the mold designer can see what he is doing. See page 60.

The second step is a thorough consideration of all the problems of shrinkage, warpage and accuracy as detailed in Chapter 10. That chapter deals with master patterns and some molds do not use master patterns; nevertheless the interior contours of a mold always are those which a properly made master pattern would generate.

The third step is a tentative selection of mold materials in view of the injection cycle and the equipment available to the casting house, as described in the earlier parts of this chapter.

When the Mold Problem Is:	The Mold Material Most Likely to Solve It Is:	And the Second Choice Is:
Accuracy		
High	Steel	Soft metal
Low	Rubber	Any
Medium	Soft metal	Steel
Random	Rubber	Any
Selective area	Rubber-steel combinations	Rubber-soft metal combinations
Clamping pressures		
High	Steel	Soft metal steel-jacketed
Low	Any	Any
Closing		
Accurate	Steel	Any steel jacketed
Quick	Any	Any
Contours		
Accuracy more important than intricacy	Steel	Soft metal
Intricacy more important than accuracy	Rubber	Soft metal
High intricacy with high accuracy	Soft metal	Steel
Cored passages in molds	Any	Any
Cores, resilient	Rubber	Rubber members of combination molds
Distortion Elimination	Steel-rubber combinations	Any
Ejection		
With mechanism	Steel	Soft metal, steel jacketed
Without mechanism but with slight pattern draft	Any	Rubber
Without mechanism and without pattern draft	Rubber	Any
Experimental molds	Rubber	Soft metal
Fatigue of operator	Aluminum	Rubber
Fixed position molds	Steel	Any steel jacketed
Flash prevention	Steel	Rubber
Follow pattern down during shrink	Rubber	None
Guide members	Steel	Steel jackets
Heat transfer		
High	Aluminum	Any metal
Low	Rubber	Alloy steel
Slow and steady	Alloy steel	Any metal rubber jacketed
Hinge members	Steel	Steel jackets

When the Mold Problem Is:	The Mold Material Most Likely to Solve It Is:	And the Second Choice Is:
Holes in patterns		
Straight	Steel	Steel members
Tortuous	Rubber	Rubber members, resilient cores
Undercut	Rubber	Rubber members, resilient cores
Injection		
Continuous pressure	Rubber	Rubber combination
High pressure	Steel	Soft metal, steel jacketed
Low pressure	Soft metal	Rubber
Medium pressure	Soft metal	Steel
High temperature	Any	Any
Low temperature	Steel	Soft metal, steel jacketed
High viscosity	Steel	Soft metal, steel jacketed
Low viscosity	Soft metal	Rubber
Medium viscosity	Any metal	Any combination
Nozzle mating area	Rubber gasket	Steel
Inserts		
Flush	Rubber	Any
Fragile	Rubber	Spring actuated steel
Protruding	Rubber	Any
Inspection of patterns, costs minimizing	Steel	Soft metal
Maintenance of molds, costs minimizing	Steel	Soft metal
Materials of molds, costs minimizing	Steel	Any
Movable members	Steel	Steel jacketing
Parting lines		
Elimination	Steel members, movable	
Minimizing	Steel	Rubber combinations
Preparational costs of mold making	Steel	Rubber
Recoverable values of mold materials	Soft metals	Any metals
Rough handling	Rubber	Steel
Scrubbing action	Alloy steel	Steel
Set-aside station	Any	Any
Setting time reduction	Steel	Any
Spring members	Steel	Steel jacketing
Surface character fidelities	Rubber	Soft metal
Smoothness	Steel	Catalin
Toolroom costs, minimizing	Rubber	Soft metal
Undercuts	Rubber	Rubber inserts
Wear sections	Steel	Rubber

Parting Lines. The fourth step is to establish the parting lines. The entire selection of mold-making materials and methods may be established or modified by consideration of parting lines.

Parting Lines as Design Considerations. Parting lines of precision investment castings almost always are vestigial as compared to thôse familiar to sand casting. Within the scope of that word, they may be plainly visible or nearly invisible to the naked eye. In some instances they are nonexistent. Their sizes and locations can affect mold costs, molding costs and the selection of mold materials. Their locations can affect product strengths if the parting line area in a given alloy in the as-cast metallurgical structure becomes a stress riser. Their sizes, directions and locations can affect secondary operations costs.

Elimination of Parting Lines. Parting lines are not always necessary except where they might come at the extreme edges of pattern surfaces. A great many patterns can be ejected from molds, as for example, a cylindrical rod pattern can be pushed straight out through the end of a tubular mold, with microscopic parting lines existing only where caps were closely fitted to the ends of the mold. Such a pattern can be tubular if a core is fitted to one of the end caps, and the bore of the pattern may have a microscopic parting line only at the one end where the core end mated with, rather than being solid with, an end cap.

The pushing out (mechanical ejecting) is especially easy if a slight amount of draft—on the order of 0.001 inch per inch of length of the tubular mold, or sometimes even less—is permissible. Thus the product designer continually has a choice, on many patterns and many areas of patterns, between accepting fine parting lines, eliminating them by allowing slight draft on appropriate dimensions plus extra costs for ejection mechanisms in the molds, or eliminating them by allowing less or even no draft and paying for costlier ejection mechanisms.

On the bore of the tubular pattern and on many other interior contours there are other options. An investment core, either crushable or shrink restraining, can be placed in the mold as an insert. This core goes on with the pattern and through the casting process, after which it is removed and in the removal is destroyed. Since this core must be pre-molded and its placing may increase the intricacy of the mold and of the molding cycle, it increases the cost.

A resilient rubber core may be attached to one of the caps. Upon withdrawing the cap this core will stretch thin and come out. Because of the reduction in its diameter when stretching, it needs no draft. There will be a faint parting line at the end where it bears on the other cap. That line will increase as the core wears. Wear will be more rapid than for a solid core; therefore this practice tends to increase molding costs.

The resilient core may be arranged to be cemented to the second cap at the closing of the mold, or to fit by slight compression into a recess in that cap. Either of these methods eliminates the parting lines at the bore but results in rapid destruction of the core, sometimes in the destroying of one core for every pattern, and thus increases the molding cost.

Minimizing the Parting Lines. On certain contours of some patterns, parting lines are inescapable. On others it is more economical to have than to eliminate them.

The size and visibility of the parting line is directly related to the accuracy of the mold, and the accuracy to the cost.

Options of Parting Line Positions. Inspection of the blown-up drawing, perhaps aided by a few measurements and a little solid geometry, will show the obvious positions for the parting lines. Anyone who has designed patterns for sand castings can do this very quickly. But there is a difference. Precision investment castings are not so likely to be redesigned for the purpose of creating favorable positions for parting lines.

Careful inspection of the drawing may show that there are many options as to positions and directions of parting lines. These options become product design options, but they affect the costs of molds and of molding.

If the product is a simple cylinder, for example, the parting line can run axial to (lengthwise of) the pattern. Removing the pattern from the exterior members of the mold is a simple matter of lifting off one half of the mold and lifting out the pattern. But there may be objections to this direction. If the parting line is a stress riser, the working stresses of the product may tend to compound themselves in that direction. And this parting line is the longest one which readily can be produced on that product.

There also may be secondary operation objections. Such a parting line could be shock damaging to a carbide tool which was machining an extremely hard alloy. And the presence of that line would be far from ideal for centerless, or any other grinding.

The parting line could run around the circumference of the cylinder, be radial to the axis. Removing the pattern from the mold exterior would be a matter of pulling the pattern members lengthwise. If the stresses on the casting were tensile, such a parting line might be undesirable as a stress riser. If the stresses were shear or were fatigue (vibrational), the line might be located where those stresses were light, since the parting line could be at any point along the piece. And since the line need not follow a truly circular course but can be arranged to follow an elliptical or any other varied course at little or no extra cost, the stress effects are still further controllable.

Such a line would have no serious effect upon a carbide or other machining tool. Although it might tend to dress a groove in a straight plunge-cut grinding wheel, the effect would not be serious and there would be no bad effect upon any grinding method in which there was axial movement or reciprocating movement between the face of the work and the face of the wheel.

The interior parting line of the cylinder would be radial. It is possible but seldom practical to produce a lengthwise or axial interior parting line.

If the exterior line also were radial, one motion could serve to pull interior and exterior members of the mold free of the pattern. But if the exterior line were axial, there would be one motion, or set of motions, to remove the exterior members, and a second motion to remove the interior ones.

Stress problems would differ. If the exterior line were axial, it might be a riser for stresses in one direction while the interior line was a riser for stresses in the other. But if all stresses were in such directions as to affect radial parting lines, the interior and the exterior lines could be put at such locations in relation to each other as not to compound each other as stress risers.

Metallurgical and Mechanical Options. For the sake of simplicity the foregoing discussion has omitted the options of using mechanical motions within the mold to machine away the parting lines, and of using superior alloys in the castings to eliminate any problems of parting lines as stress risers. Mechanical motions, especially those which chase threads, can be highly valuable.

The metallurgical options never should be out of the mind of the precision investment casting designer.

Separate Section Options. With the parting line axial to the cylinder two directions of withdrawal of mold members were necessary, one vertical to the axis for removal of the outer member and one parallel with the axis for removing the inner members. More than 20 directions of withdrawal have been known for members of individual molds. The resulting molds were equipped with slides, guides, pivots and hinges until they became a toolmaker's dream.

At some point in such a design, and usually at a much earlier point than the average mold designer considers, it becomes advisable to break up the pattern into separately moldable members and to join them into the final pattern.

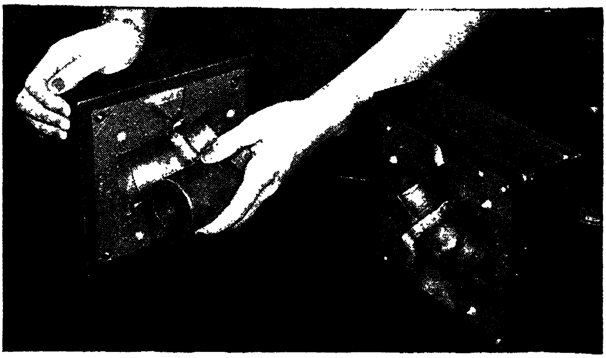


FIGURE 89. Separately molded inserts can reduce interior parting line troubles.

Separable sections have the advantage that many of them can be molded without parting lines. Still more can have the parting lines brought to extreme edges. The need to alter the contours of one section in order to withdraw the mold members from another is eliminated. Slight positional, contoural or dimensional alterations to compensate for warpages experienced in casting are easy to make.

Joining the separable sections into final patterns may be done by several methods. Among them are:

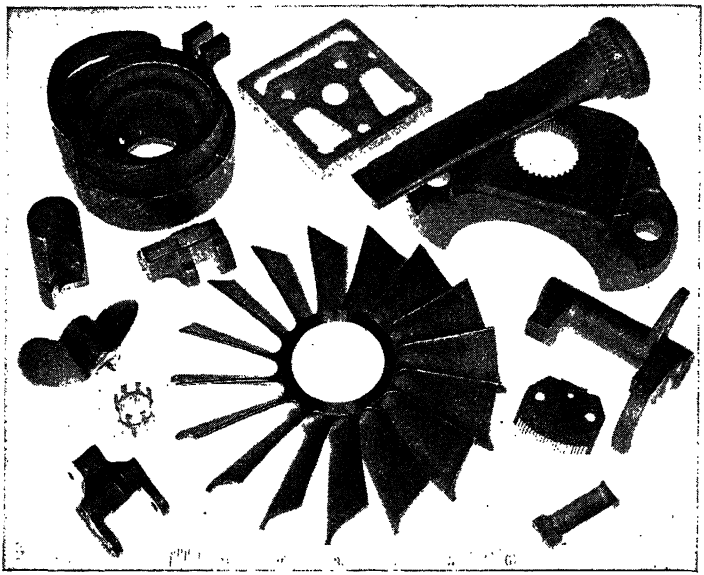
(1) The *preferred* method is to soften the mating surfaces with a hot tool and stick the sections together.

(2) The *most accurate* and often the least costly method is to use the members as fragile inserts in the main mold, or turn that mold into a device for simultaneously fastening the members. See page 183.

(3) An alternative method is to glue the members together with common glue which may be purchased at any hardware store. The glue requires a few hours' drying time, but will evacuate from the investments without difficulty. Fish or animal glues are preferred, the pyroxalin and other plastics types sometimes being explosively hazardous during the melt out.

How Rubber Molds Are Made

The making of a rubber mold is a matter of forming and vulcanizing. The forming is done by metal members. Vulcanizing is done by heat and pressure applied by metal members. The rubber is of a special type intended for precision investment casting usage and for rubber molds used in the plastics industry. There are several formulas for these rubbers, including some of the synthetic rubbers. Vulcanizing methods vary somewhat with the formulas. The rubbers and the formulas for vulcanizing them are to be had from the mill supply houses which specialize on the precision investment casting industry.



(Courtesy Allis-Chalmers Mfg. Co., Milwaukee, Wis.)

FIGURE 90. The intricate contours of impellers usually require rubber molds. But patterns for the other products shown here were molded in metal.

Rubber molds are less dependent upon exact placing of parting lines than are metal molds, because the rubber can spring or stretch slightly to clear the pattern. If this is desired, any mold-making method which includes two vulcanizations of one mold section should be avoided.

Rubber is capable of as infinitesimal parting lines on the patterns as any metal. If this is required, any method calling for two vulcanizations of one section is to be avoided, since the second vulcanization distorts the section and increases the parting line area.

Preliminary Steps. A suitable master pattern must be prepared. Since this can take part in the transfer of vulcanizing heat, it should be made of metal, although other materials can be used. See Chapter 10.

If expansion and contraction of the rubber is used for controlling the accuracies and contour fidelities of the pattern, the amounts and directions of this must be estimated. See page 191.

Suitable metal devices for controlling the outside dimensions and contours must be provided. These may be simple open frames, like boxes with both lids removed, but made of metal. Or when the contours are to be more closely controlled in order to control the resilient action of the mold or to fit the mold in as a resilient member of a metal mold, the inner contours of the frames or boxes must be fashioned accordingly.

The inner dimensions of the frames or boxes must be such as to clear the master pattern by at least 0.25 inch at all areas. There are occasions when less clearance is provided in order to obtain thinner wall sections for expansion and contraction control or to fit the rubber members into metal molds. But the 0.25-inch clearance is the general minimum.

Means must be provided for separating mold sections to keep them from vulcanizing together. French chalk will do for most occasions, but thin metal shim stock or foil sometimes is needed, especially for high accuracy work and when several sections of a mold are to be vulcanized simultaneously.

A standard vulcanizing press, or a vise having plates which can be heated to vulcanizing temperatures, is also needed.

Slab Method. This is useful for experimental molds and for some operating molds. It is unsuitable when there are severe undercuts or other intricate interior contours on the master pattern.

Unvulcanized rubber is procured in such consistency that it can be cut or pressed into slabs. One slab is cut to such dimensions that when the master pattern is pressed down in it to the parting line there will be at least 0.25 inch of rubber at all areas which are within the rubber. The master pattern is pressed down to the parting line in this slab. The slab is dusted with a thin layer of French chalk. The dusting must cover all of the exposed rubber surface.

A second slab is cut of thickness to cover the upper half of the master pattern plus at least 0.25 inch of rubber on all sides. This slab is pushed down on the master pattern until it fully meets the surface of the first slab.

The open-sided frame is so applied to both slabs that it covers their parting line but allows a slight amount of rubber to protrude at both open sides. The assembly is taken to the press and vulcanized. The slabs are ripped apart at their mating surface. The master pattern is removed. An experimental mold often can be made in 15 minutes by this method.

Section on Section Method. This is a quick method which will take care of more intricate interior contours than are practical for the slab method, but it has the defect of double vulcanizing one section.

Unvulcanized rubber is procured in highly plastic consistency. A suitable metal box having two halves is prepared. One half is filled with plaster of Paris or any other material which will harden and withstand vulcanizing temperatures. The master pattern is pushed into the plaster of Paris to the parting line. The plaster of Paris is allowed to set.

The other half of the box is filled with rubber. The master pattern in the plaster of Paris is pushed into the rubber until the rubber meets the parting line and is against the plaster of Paris face. The assembled box is taken to the press and the rubber vulcanized.

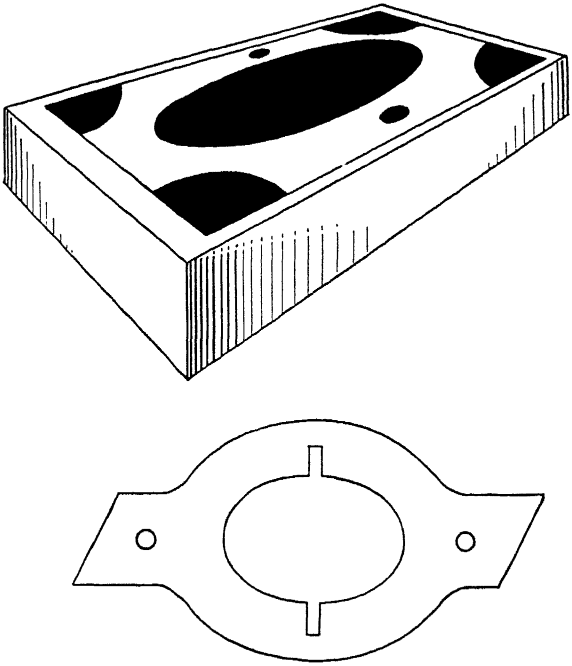
The master pattern is removed and all plaster of Paris is removed from the master pattern and from the box. The master pattern is replaced in the chamber which has been produced in the vulcanized rubber.

The empty section of the box is filled with unvulcanized rubber. The vulcanized rubber face is dusted with French chalk. The vulcanized rubber now is a holder by which the master pattern is forced into the unvulcanized rubber. The entire box is taken to the press. The unvulcanized rubber is vulcanized. The two sections of the mold are ripped apart at the parting line.

The Shim Cradle Method. This results in the most nearly invisible parting lines, and if there are to be two or more parting line planes, permits all sections of the mold to be made and vulcanized simultaneously.

Using all metal shim stock, not over 0.003 inch thick, one separator is prepared for each plane of parting of the mold.

Each separator is so dimensioned that it will bear against the box at the bottom or a side, and if necessary for guiding or stiffness of assembly, at one or more sides of the box. The center of each separator is so cut out that at the plane or cross section at which it crosses the master model it will clear the model by at least 0.125 inch on all sides of the model. The separators may need to be slotted so they may be assembled into a cradle or crib construction. But each separator must be punched or otherwise so contoured that there will be space for rubber to pass through or about it at the exterior of the mold, as otherwise the rubber which will pass through the clearance from the master pattern will bend outward as the mold is closed.



Single shim in place on rubber.

Shim slotted for assembly of transverse shim member.

Figure 91.

Very often the cradle is best made experimentally of stiff paper to make sure that its members can be fitted together about the master pattern. The paper sections then can be used as templates for cutting out the shim stock. The cradle is assembled with the master pattern inside it and is placed in the bottom half of the metal box.

Unvulcanized rubber is added, making sure that it fills up all parts of the bottom of the box. Within this soft rubber the pattern is moved with the fingers until it clears all parts of the cradle by the planned 0.125 inch and every parting line area is aligned with the cradle member intended to produce it. The depth of this bottom "half" of the box should be as high a proportion of the whole depth of the box as is practical for working. This is a matter of judgment, sometimes of experiment.

When the rubber has been slowly brought up to the top of this box member, with the position of the master pattern checked carefully at every step, the top half of the box may be filled with soft rubber and gently forced down over the master pattern. The box with its contents is carefully and gently placed in the press. The rubber is vulcanized. The box is removed.

With a thin-bladed, sharp knife, working only on one side of each separator, and keeping the blade bearing constantly against the separator, the rubber is cut through to the master pattern. This is a skilled operation and should not be performed by a man who is in a hurry. When the cutting is finished the mold sections will separate at the true parting lines. The cradle sections usually are torn apart and destroyed when finally cutting through to the master pattern. Of course, if only one parting line is needed, only one separator is made and there is no crib or cradle.

How Metal Molds Are Made

Metal molds may be made from the solid, beginning with the most convenient or economical shapes such as rounds, flats, hexagons, channels and tubes and using ordinary toolroom methods.

Casting Methods. In Chapter 10 several methods for using precision investment casting for the development of molds were described. The ones most highly recommended are toolmaking in wax, die making in wax, die hobbing in wax, and die building with wax.

Electroplating and Metallizing. Mold members may be built up by making master patterns and then either selective electroplating or metallizing upon them. Mold cavities may be made oversize by experimental casting or otherwise, then electroplated or metallized down to size. The values of these resources depend upon the skills and equipments of the contract shops which do the work.

Soft Metal Mold Making

Soft metal molds are made of Cerro Alloys, pure tin, Woods Metal, type metal, Kirksite, lead, Meletts Metal, and others. Most of these are low fusing-point alloys. The best of them, or at least the most readily workable of them, show no discernible shrinkage upon solidifying and cooling. But care must be taken that their softening ranges are not below the molten temperature or the injection temperature of the pattern material.

The actions of these alloys under pattern-making methods must be studied very carefully in the literature. Some of them can be hobbed readily; some only enough so that hobbing can be a mild corrective operation; some will crumble or fracture under the hob. Direct inquiry should be made to the producers of these alloys.

High Pressure Casting. The most common method for making these mold cavities is hydraulic pressure casting, and the most commonly used alloy is Cerrobase (58 per cent bismuth, 42 per cent lead).

The pressure casting process is similar to general hobbing procedures. The master pattern is embedded in a matrix to the parting line (or to one of the parting lines), and is placed within a hydraulic chamber capable of withstanding 5 tons of pressure, with the pattern extending upward to act as a hob. The molten metal is poured into the chamber so as to cover the master pattern and fill the chamber to the desired depth, and the hydraulic pressure is immediately applied to the metal.

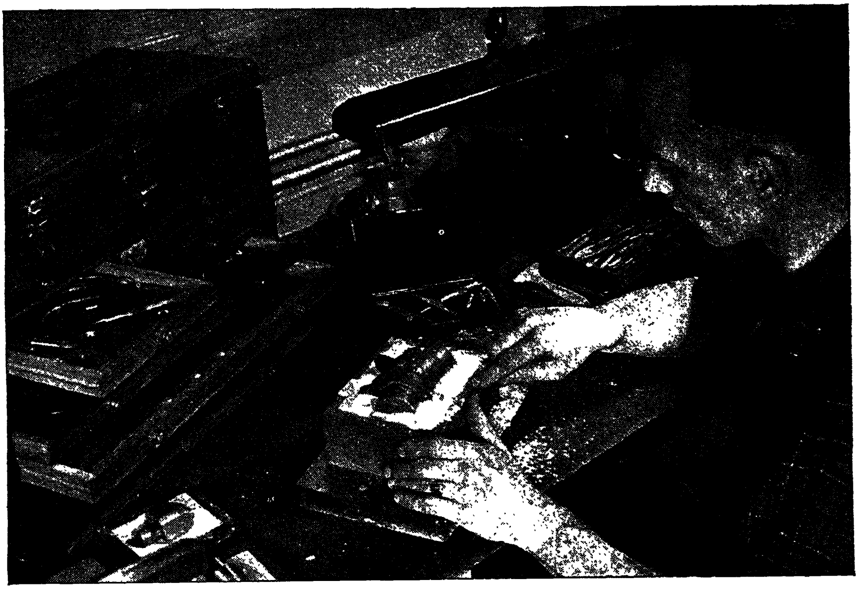


FIGURE 92. Embedding a master pattern in plaster preparatory to pressure casting the top half of the die.

Principal effect of this procedure is to cause the metal to cover thoroughly or "wet out" the surface of the master pattern, thus producing a mold cavity surface which faithfully reproduces the contours and the surface character of the master pattern.

From this principal benefit comes the principal trouble. If not embedded with high accuracy to the parting line, the master pattern will not pull out of the soft metal after casting. This trouble usually is debited to failure of the master pattern to be smooth and accurate. But the fact is, the entire procedure requires such high accuracy that it is unusual for a toolmaker to be able to make more than one mold in one day.

Chapter 12

Dispensable Pattern Materials

The selection of dispensable pattern materials is one of the most individual matters in the precision investment casting business, nearly every casting house having its own ideas about it.

Economically, the pattern materials have about the same effects upon costs as the costs of cutting oils have upon the costs of machining or those of molten salts have upon salt bath heat-treating. About one-eighth of a pound of material is consumed, on the average of several houses, for each pound of steel shipped as castings, or about three-eighths of a pound for each pound of aluminum castings. Costs of materials can vary enough so that the highest cost material used ranges up to 500 per cent of the price of the lowest, with 300 per cent a fair average, but the higher cost materials generally are used for more intricate castings which sell for higher prices. And the costs of pattern materials as compared to raw materials metals prices are tending to come down.

Historically, most of the pattern materials have been waxes or mixtures of waxes and other materials. Low melting-point metals have been tried, and so have ice, frozen mercury and some of the plastics. Each of these materials, and especially the plastics, is used to some extent. But waxes or mixtures of waxes and plastics predominate.

During the earliest period of the process, molding methods were crude. If the cavity contours were correct and accurate, it was believed that any failures to achieve accuracy in the castings must be due to chemical or physical faults in the pattern materials. This was bolstered by a general belief that wax remained a liquid at any temperature, that at its solid temperatures it merely was a liquid of higher viscosity than at its fluid temperatures, and that accordingly it did not go through a freezing range during which it had to emit latent heat of fusion in order to solidify. Failures to behave in this way were debited to impurities in the wax.

Such a "perfect liquid" would shrink equally in inches per dimensional inch in all directions as it cooled. Wax failed to do so, of course, in the molds. Aside from the effects of impurities this failure was debited to coefficient of friction between the wax surface and the mold surface. Lubricants were tried. It was found that they had excellent effects upon low pressure injection but much less upon sectional shrinkages. See page 188.

Injected waxes insisted upon behaving much like cast metals. They had mushy ranges, selective solidification ranges of various elements with consequent segregation troubles, progressive deposition, higher accuracies at areas of original solidification, critical temperature ranges during which they reversed their directions of temperature change and also their directions of expansion or contraction. Restraint while cooling resulted in residual stresses which made the waxes weaker when cool and often resulted in plastic creep or "season warpage."

The years of experimenting in attempts to obtain waxes which in the molds would approach the theoretical behaviors of perfect liquids were beneficial. They showed what results could be had with various mixtures, and how the waxes and other pattern materials would behave when cast.

Most pattern waxes are at least 50 per cent specially prepared petroleum waxes, usually of the paraffin family. Other wax ingredients include carnauba, ouricuri, candelilla, beeswax, japan wax, spermaceti, Bergundy pitch, palm wax, and synthetic resins. Plastics most commonly used as pattern materials are polystyrene, methyl methacrylate (Lucite), and polythenes.

Sources of Materials. It is a rare precision investment casting house which buys raw materials and mixes its own pattern materials. That process is best performed by houses which sell waxes and other products in thousand-ton lots to other industries rather than the thousand-pound lots which are big orders for most casting houses. Specifically, pattern materials are best purchased from houses which process them especially for the precision investment casting industry or from jobbers which serve that industry. But those materials may be blended by the casting house to obtain special effects.

Dyeing of Materials. The average casting house continually uses at least two different pattern materials. One is soft and highly fluid and intended for thin sections of intricate contours. The other is harder and less fluid and intended for thicker sections with less intricate contours. The latter is commonly less expensive and also can be handled more roughly. Each of these is dyed a distinguishing color for the guidance of operators and supervisors. In addition there will be reclaimed material but this ordinarily is easy to identify because its color is "off" those of the others. Some houses use eight or more materials, each of which has its own distinguishing color. The dyes have no effect upon the performance of the material. Any dry pigment dyes may be used.

Melting Points. Pattern materials are considered to be solid at room temperature (70 to 80 degrees F) although some are more plastic than others at that temperature. As they are heated they go through ranges, a range being characterized by the practical effects of pressure as experienced in injection machines and the effects of physical states as experienced in mold behavior and within investments. In short, a "range" is a practical, and not a theoretical matter.

The ranges are, in general:

(1) *Solid.* The material will not flow through the orifice of an injecting machine unless under pressures too high for practical application. Those pressure limits may be as high as 50,000 psi, but rarely are over 3,500 psi and 100 psi is normal or average.

(2) *Solid-critical.* At various points as its temperature is raised, a material may go through critical ranges similar to those of heat-treatable steels, but not so consistent in their characteristics. In such a range the material may become cooler than the heating medium, and may contract slightly, expand more slowly than it had been doing, or expand more rapidly, depending upon the material. These solid-critical ranges can impose serious strains upon investments. Pattern materials can be so balanced that one ingredient compensates for the critical range of another, or one is in its softening range before another gets into its critical range and therefore the critical ranges impose their movements upon softened pattern material and not upon hard and somewhat brittle investment material.

(3) *Softened.* The material will flow through the orifices of an injection machine under pressures practical for the machine to apply, but will not flow by gravity. This range is useful for injecting, and the higher the temperature the less the necessary pressure. This range also protects the investment material against some of the worst effects of high temperature expansion of the pattern material.

(4) *Mushy.* The material contains some ingredients which have become fluid and some which have not. It may or may not flow slowly by gravity. This range is likely to give unpredictable effects if used for injection, but solves some of the problems of the effects of pattern expansion upon the investment during the melt out.

(5) *Fluid.* The material contains no hard or plastic ingredients and will flow readily by gravity. This is the only range which is useful for low-pressure injecting.

(6) *Minimum viscous.* The material has become so fluid that it will penetrate the pores of the investment and will retreat from the cavity surfaces, leaving those surfaces clear for the escape of air when metal enters the cavities. This effect can be measured only by cooling down an invested flask which is ready for pouring, sawing it into sections, and observing the stained areas to which the material has escaped.

These ranges can be varied widely and are highly controllable. The characteristics desired in the ranges differ with casting problems.

High vs Low Melting Point. There is no absolute dividing line between high and low melting-point pattern materials. But it is generally accepted that if an operator gets fluid pattern materials of temperatures below 170 to 175 degrees F on his hands, he is likely to be stung, but less likely to be burned. At any higher temperature he is likely to be burned. Therefore materials which are mushy or fluid at less than 175 degrees F are called low melting-point and all others high melting-point materials. Low melting-point materials may be more plastic at room temperatures on hot days and therefore more subject to handling damage, but this is not true of all low melting-point pattern materials.

Sharp Melting Point vs Wide Softened and Mushy Ranges. The complete softened and mushy ranges can be less than 10 degrees F or can be as wide as 75 degrees F. If injection is to be at the fluid range, the narrower the softened and mushy ranges the better so far as injection alone is concerned.

Narrow softened and mushy ranges also are beneficial within the molds. The wider these ranges the longer must be the dwell time of the mold at the injection nozzle.

Wide softened ranges are beneficial when it is desired to inject at varied but controlled temperatures for differing section thicknesses and differing accuracies, this being especially true if the injector is capable of no more than 100 psi. The higher the temperature and the greater the softness, the more rapidly the injector will fill out a heavy section, and the more completely it will fill out intricate contours. But the lower the temperature, the less the shrink within the mold, and the higher the accuracy. A wide softened range provides many injection options.

A sharp and narrow softened range can be helpful when it is desired to inject at a constant pressure and temperature. At too low a temperature the material will not inject.

Long softened and mushy ranges impose less strain on the investment during the melt out. With the exception of the ability of the pattern material to expand itself out through the gates, runners and sprues, or to flow plastically through those passages, the investment must withstand the entire thermal expansion of the pattern material and this can be as high as 9 per cent of total volume on some materials. This factor explains the modern trend toward injecting at softened rather than at fluid temperatures.

Rough vs Gentle Handling. Most patterns are handled gently after being molded and are not stored for long periods. But in some shops and on some products it is economical to handle the patterns almost as if they were steel and to store them in bins or boxes like any semifinished materials. For these purposes, outright plastic materials generally are superior although some of the wax-base materials also are resistant.

Patterns to be handled roughly may neither be soft nor brittle. When there are extremely long, thin and delicate members, ability to withstand handling may outweigh all other factors in the selection of a pattern material.

Recoverability. Nearly all shops recover up to 60 per cent of their wax from the melt out and use it in sprues, runners, risers, and for heavy sections of patterns which are molded in separate sections. This material may be regarded as having practically no cost since the cost of bringing it to the remelting equipment is no greater than that of placing it in the trash can. And about 60 per cent of the weight of the average cluster is in these members.

Some of the larger shops also use recovered wax for nearly all patterns. They are able to recover 75 per cent of their wax. The cost of filtering, testing, and adding other waxes to obtain the desired operating characteristics is about one third of the ordinary cost of new wax. But the filter equipment cost, the laboratory checking cost, and the labor costs are high enough so that this operation usually is not considered profitable unless at least 2,000 pounds of wax a month are to be processed.

Waxes of some types cannot well be recovered for use in the patterns themselves. These types lose volatiles during the melt out and sometimes during the molding.

Plastics of the kinds ordinarily used as pattern materials have no recovery values for use in either sprues or patterns. But plastics of kinds which might be recovered could be used as pattern materials.

One large shop reports that its wax could not be recovered at a profit unless all of the shop procedures were clean enough to keep down the filtering cost and that therefore the recovery has a disciplinary effect and promotes good housekeeping. Another shop has found that the recovered wax has lower shrinkage in the mold and a longer mushy range in the invested flask and therefore this wax is carefully preserved and is dyed a special color to identify it for use in heavy sections where those properties are most valuable.

Quick vs Slow Setting. As compared to most metals, pattern materials are slow conductors of heat. Assuming that they have been injected at fluid temperatures, the pattern materials must go through a series of conditions before they are ready to be clustered. It must be remembered that these conditions are not the theoretically perfect ones in which the materials are agitated to prevent supercooling (mechanical agitation would be impractical within the average mold), but are the practical molding ones in which plenty of supercooling takes place. The conditions are:

(1) The areas most readily chilled by the mold cool to the mushy range.

(2) The solidified elements of the mushy range deposit themselves; they are segregations.

(3) This process progresses into the liquid portion.

(4) The solidified elements as they have solidified have given up their latent heat of fusion.

(5) Other elements are solidifying, giving up latent heat of fusion, perhaps in so doing remelting some of the solidified portions.

(6) Solidification becomes complete at the areas most completely cooled by the mold. Solid-critical areas begin to be crossed, with resultant mechanical actions and thermal actions within the material.

(7) The entire surface of the material becomes solidified, and as a poor conductor of heat, presents a thermal barrier to the heat trying to escape from the internal portions.

(8) The surface holds some of the heat conducted to it from the internal portions; therefore remains somewhat soft.

(9) The expansions and contractions of the inner portions passing through their critical ranges cause motion at the surface areas.

(10) The surface portions in attempting to contract while cooling are imposing compressive stresses on the inner portions, but also are receiving tensile stresses and are taking something of a permanent set.

(11) The inner portions cool and contract, and in so doing seek to pull down and contract the surface areas against the permanent set which the surface areas have taken.

(12) If some of the elements did not remain soft and plastic at this point the surface would crack, or else the interior portion would have shrink voids. But some plasticity remains until the interior is fully cooled. At this point the pattern has "set" and may be handled.

Examination of that sequence will reveal several factors:

(1) If the material is injected at softened rather than at fluid temperatures the sequence begins at step (7) and many of the troubles never occur.

(2) The troubles are in direct ratio to thickness of sections, since the thicker the sections the greater the thermal barriers which the exteriors form against the interiors.

(3) The troubles are controllable to a large degree by controlling the mold temperature and thereby the plasticities of the surfaces of the patterns.

(4) The sequence requires time. This time is provided by the set-aside time of the mold and the seasoning time of the pattern.

Pattern materials can be made quick-setting, or slow-setting, or be given various setting times. The quick-setting ones are necessary for high-speed injection machines at which the mold stays in place and cannot be moved for set-aside time and the mold must be opened quickly or the machine cannot be high in injection cycle speed, as for example, for 80 injections a minute. But shops generally report that with sections of over 0.125-inch thickness such high speeds become impractical. As sections become thicker, set-aside time has to become longer; as long as 25 minutes for the average 0.50-inch section and three days for a 5.0-inch section have been reported to be necessary. In these cases high-speed equipment must include multiple molds so that several cavities or patterns are injected simultaneously, and several molds per injector operator in order that the molds can be passed along to a set-aside station.

Highest-speed setting usually involves injection at the bottom of the softened range and injection pressures on the order of 3,500 psi or more, far beyond the 100-psi limits of a great many injectors.

Patterns made of some quick-setting materials become dangerously brittle if allowed to cool below 80 degrees F. The requirement is that the patterns be kept at controlled temperatures until invested. On long production runs with adequate shop mechanism this is not difficult, but on short runs and during cold weather it can be bothersome.

Patterns made of slow-setting materials can be time-consuming if injected into uncooled molds on hot days. A changeover to a quicker setting material may be indicated. But controlling the mold temperatures by water cooling or other methods never is difficult and always is good practice.

Temperatures vs Interrupted Production. Some materials will lose volatiles and become brittle if kept at their fluid temperatures for more than a few hours. These same materials do not become brittle at their softened ranges. For non-continuous operation of the injector the softened range therefore may be preferred.

Volatility. So far as is practical all pattern materials should be completely volatile in the melt-out procedure.

Injection Methods

The pattern material and the injection method and equipment must be suited to each other. And since no one type of equipment can be ideal for all purposes, there must be different types of pattern materials.

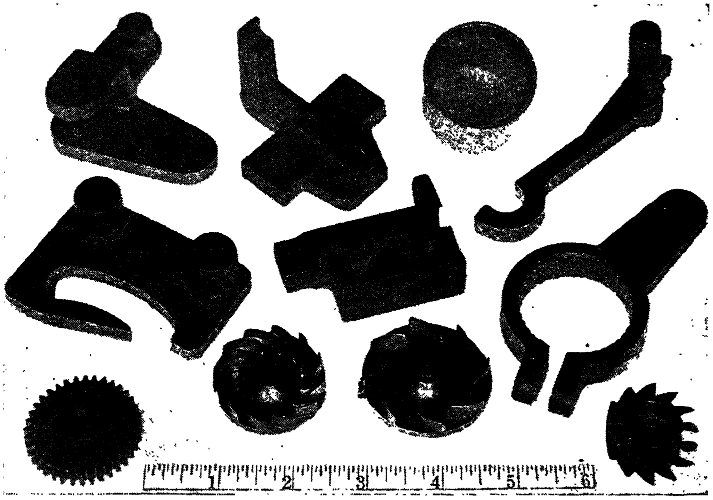
The three most common methods of injection are centrifugal, gravity and pressure. Of these the pressure types are predominant in industrial plants. But the others have advantages for some purposes.

Centrifugal Injectors. The pattern material usually must be at fluid temperature. It is held in a container at the axis of the centrifuge. The container either must be supplied from a bulk container and fed the exact amount required for each charge, or else must have valve mechanisms which release only the amounts wanted for each "shot" into each mold.

The position of the mold may be adjustable along the arm which supports it, thus making the radius and the corresponding centrifugal force at a given rpm controllable. The rpm also may be controllable but generally is not, this being a serious fault with the applications of many of these machines to molds which need close control.

Power is by spring motor or electric motor. There must be an automatic cutoff when the desired number of rpm have accomplished the filling of the mold and the necessary dwell period, and for ideal operation this should be followed by controlled braking action to conserve the time of the machine. Machines can have as many arms and therefore can fill as many molds at one time as desired.

Pattern material as it leaves the central chamber is subject only to the force of the rpm at the radius of emission orifice. Usually it is moving quite slowly. As it moves farther out and reaches greater radius it accelerates in speed. The acceleration is not in true relationship to the centrifugal force, the material being retarded somewhat by friction. If the machine is a constant rpm type, the injection force can be increased only by moving the mold farther out along the arm, thus increasing the travel distance along which the pattern material is subject to friction. The friction will induce eddy currents which are to be overcome only by the viscous shear of the material, and these currents can result in turbulent action of the material with entrapment of air which will cause troubles in the molds and in the patterns. Those troubles usually are debited to the molds or the materials.



(Courtesy Allis-Chalmers Mfg. Co., Milwaukee, Wis.)

FIGURE 93. The making of patterns for no two casting designs involve exactly the same problems.

If the machine is controllable as to rpm as well as mold position, the acceleration may be had without such great loss and trouble from friction against the pattern material.

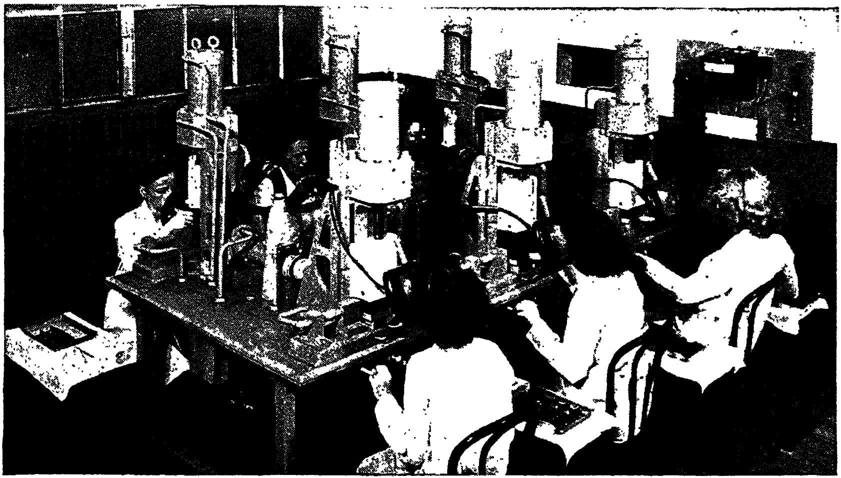
The material as it enters the mold has both pressure and velocity. It tends to fill the extreme end of the mold first and to begin its solidification at that area; therefore centrifugal injection is capable of high control accuracies at selected areas. If the material is capable of separation and segregation, its heavier elements will be driven to the outer end and thus will increase the accuracy at that end. Filling will be from the outer end backward, with the centrifugal force tending to fill every slightest indentation that can be reached by the material. For this reason centrifugal injection can contribute high values to the fidelities with which surface contours and characteristics of the mold cavities are reproduced in the patterns.

The mold cavities usually are in directions more or less transverse to the centrifugal axis. As the pattern material enters them, it tends to repeat the selective deposition process, depositing first along the walls most remote from the centrifugal axis. The laws of centrifugal force as complicated by the hydrodynamics laws of fluid friction are highly complex and will not be discussed here. But in general, if there are any heavier elements in the pattern material, they will tend to appear in layers along the mold cavities with successively lighter layers on them. This can impart directional strength to the pattern, the strength being in a direction transverse to the centrifugal radius. Directional strength rarely is detrimental to the pattern, and if taken advantage of, can contribute desirable values to the strengths of thin and delicate members of patterns.

Patterns can be so arranged in the mold that the material travels down a central passage, travels through a transverse passage, and then by maintaining a superior volume of material in or at the central passage, the material is forced to fill the mold chambers in a direction contrary to that of the centrifugal radius. This results in a cavity-filling action which employs the centrifugal pressure but is less subject to the velocity induced by acceleration. In the words of one caster, "the material squeezes in instead of flying in." This reduces the directional strength effects and also some of the air entrapment effects.

Gravity Molding. The fluid pattern material simply is poured into the mold, care being taken that the air can escape in a direction contrary to the pouring. This sometimes is a preferred method for molds which have been loaded with premolded fragile insert sections when the purpose of the pouring is to cement these together with the least possible application of pressure which might distort, fracture or dislodge them.

Pressure Molding. Direct pressure molding is, or can be, free of the velocity and the segregating effects of centrifugal molding. It is the only method which appears to be practical for the highly desirable molding at softened rather than at fluid temperatures. It is both simple and sensitive in control. Therefore well over 70 per cent of all industrial precision investment casting dispensable patterns are direct pressure molded.



(*Courtesy Kerr Mfg. Co., Detroit, Mich.*)

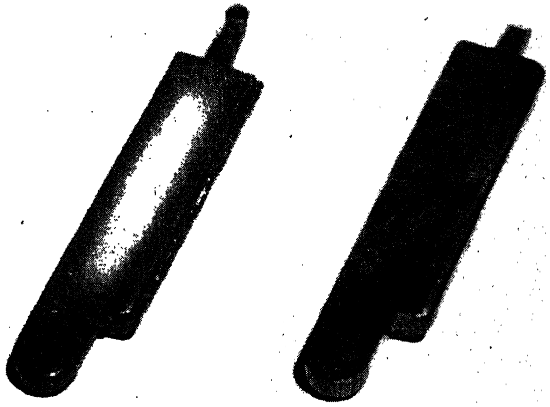
FIGURE 94. These are high-speed semi-automatic machines injecting quick-setting pattern material at the bottom of its softened range.

The pressure can be applied by pneumatic or by hydraulic force. Pneumatic appears to be practical only up to 500 psi, and many pressures must be higher than that. But pneumatic is generally, although not necessarily, more rapid in action. Hydraulic fluid being nearly noncompressible while air is compressible, it is difficult to shut off the pneumatic pressure instantaneously but fairly easy to do so with hydraulic pressure, and it is easier to vary hydraulic pressure instantaneously and sensitively; therefore hydraulic pressure is generally more sensitive in control than pneumatic. But the values of this sensitivity are not always significant. The comparison factors are like those of any machine tool controls.

There is no valid reason why pressure should not also be applied by mechanical motions such as pistons and helicoids, nor why electric motors which apply constant torques even when their shafts are not revolving should not be used. The pneumatic and hydraulic forces simply seem to be more convenient.

Ordinary grease guns have been adapted, and so have lever-actuated compression grease pumps.

Ideal Pressure Type. The ideal type of pressure injector described here is a combination of elements and practices found in many casting houses. No such machine is known to have been devised or to exist. Every pressure injector therefore is a modification of this ideal. And every modification may either require compensations in the molding practices and in the types and characteristics of the pattern material, or on the contrary may be actually superior for some applications. The ideal machine never is completely ideal or completely feasible.



(Courtesy Kerr Mfg. Co., Detroit, Mich.)

FIGURE 95. The pattern at the left was gravity poured into a mold. Its middle area shows a long, pale-colored sunken section where its surface lost the battle against the shrinking interior. Other areas are pitted. The pattern at the right was injected under 50,000-psi pressure and at the bottom of the softened range. It has no significant defects.

(1) *Material supplies.* There must be one or more bulk reservoirs holding pattern materials at such temperatures and pressures that they can be instantly supplied to the primary working reservoir.

(2) *Variability of materials.* The primary working reservoir must be capable of working when containing only a few pounds of material in order that the pattern material in use may be changed readily. All parts from the entrance of material to the primary working reservoir and on to the mold nozzle must be quickly interchangeable or else cleanable to facilitate changing of pattern materials.

(3) *Injection nozzles.* There should be at least four injection nozzles or connections for them in order that several molds may be filled succes-

sively or selectively and one mold be filled while another is dwelling. An even larger number of nozzles may be necessary.

(4) *Infinite control at nozzle.* Because control is most complete when applied to small quantities of material, there should be independent controls immediately at the injection nozzles. These controls should be independently and infinitely variable as to temperatures, pressures and velocities of the materials. And since it often would be advantageous to vary these factors for filling various portions of the mold and for dwell time, the pressure, temperature and velocity should be capable of infinite adjustability of timed cycles.

(5) *Overall pressure and temperature.* Every element, beginning with the bulk tanks and ending with the injection nozzle, should be capable of exact control of infinite increments of pressure and temperature. The controls of the two factors should be independent, but capable of being synchronized if desired.

(6) *Area temperature.* Since it is not the best practice to hold pattern material at injection temperature for protracted periods, nor to heat and then cool it previous to injection, the bulk tanks should be held at temperatures not over 100 degrees F, the primary working reservoir at not over 115 degrees F, and the injection nozzle area should supply the final injection temperatures. These temperatures apply to the pattern materials in most common use, but entirely different ones might be applicable to other materials. The preferred injection temperature with most materials, when obtainable with the injection equipment in use, is on the order of 135 degrees F.

(7) *Area pressure.* The pressure generally would have to be higher as the temperature is lowered. For most pattern materials the pressure range would be high enough if infinitely adjustable from zero to 15,000 psi at any element, with 3,500 psi the ordinary top limit of the injection range; but many molds injected at pressures ranging all the way from a few ounces to over 10,000 psi. For some materials and molds the 15,000 psi limit might not be high enough.

(8) *Controls.* Controls should be full automatic for the injection of 100 or more patterns which required the same pressure-temperature-velocity cycles, and always full automatic as to the precise measuring and limiting of the amounts of material injected into any one mold. Warning signals of any failure of the mechanism to operate properly or of a mold to fill properly should be full automatic. But for setting up and for occasional uses, manual controls also should be provided. These should be such as to be tripped and operated by foot pedals, leaving the hands of the operator free for handling the molds.

This ideal has been approached in some shops, the missing features being lack of control of velocity as well as pressure of injection and lack of independent control immediately at the nozzle.

Some shops also add the feature that the entire mold and injection nozzle work under vacuum. While this does eliminate air problems from the molds, it is not generally considered necessary.

If these ideals are not approached in the average shop, let it be remembered that it is very rare to find the ideal automatic screw machine, automatic punch press or automatic induction heating setup. In any process whatever, the approach to the ideal is limited by practical economics. Compensations are made by tooling, by the training of operators and supervisors, and by selection of supplies. Pattern material is a supply.

Temperature Control Methods. Temperatures of pattern materials are controlled by circulating hot water, by hot water baths, by electrical resistance heaters, by recirculated air, by cold water for cooling, and sometimes by ice or even Dry Ice. Water commonly is preferred for either heating or cooling since it is steady and controllable in its heat output or removal and the temperatures desired are well within the ranges practical for it. Resistance heaters are more sensitive for application to small areas. Dry Ice is an emergency condition material, used only where extremely rapid removal of heat is necessary.

The Average Pressure Injector. The pressure injectors which are average for all shops in the sense that ordinary engine lathes are "average lathes" are simple cylinders, heated either by hot water or resistance heaters, with pressures applied pneumatically. They are capable of no more than 500-psi pressures, with normal operating pressures on the order of 100 psi. Valves and other mechanisms are usually pneumatically controlled, and capable of only one injection nozzle at a time. The injector is small enough in size so that the entire machine easily can be made semi-portable or fully portable for moving from mold station to mold station.

Plastics Type Machines. Several machines of the types generally used for the injection molding of plastics products have been modified and readapted for the injection of precision investment patterns. They usually are capable of injection pressures up to 3,500 psi, but are not intended for the lower pressures. By injecting several molds simultaneously, or molds having several cavities, they are high in production rates for long run output, but at the same time can permit plenty of dwell and of set-aside time.

Public Relations and Pattern Materials. During the melt out, some pattern materials can give off dense, malodorous smokes. Wax fumes can contain highly toxic acrylic acid. Some of the plastics bases and outright plastics can give off fumes which are dangerous to health, corrosive and even explosive. While these problems can be handled within the shop, they can be difficult if the plant is located within a residential neighborhood. And since precision investment casting rarely requires heavy equipment or the handling of bulky or heavy materials or products, many plants are so located.

Scrubbers, precipitrons and like equipment can take care of these fumes, but the installation and operating costs are more than the smaller shops care to bear.

This sometimes is a governing factor in the selection of a pattern material. Materials which volatilize readily and completely and which give off no offensive fumes in the process are preferred.

The Testing of Pattern Materials

Like steels or any other materials of industry, dispensable pattern materials are uniform only within limits. And as is the case with all materials, if the task at hand needs no more than normal uniformity, pattern materials may be purchased and used without testing. But if the accuracy of the product, the intricacy of the contours of the pattern, the speed of the injection operation, or any other production factor needs the highest of uniformity, testing must be done.

Blending also must be followed by testing. Although only a few casting houses begin with raw materials and compound their own pattern materials, nearly all houses blend materials to achieve specific properties. Most of the proprietary materials are highly blendable. But one ingredient of a blend may be at the high side of its viscosity range while another is at the low side and therefore the viscosities will balance each other and arrive at an average, or the two viscosities may be at the high sides and so tend to compound each other. The casting house needs to know the exact results of the blending so it can vary the ingredients or add others to perfect its material. Only testing will find out.

Most of the tests are practical rather than "laboratory" even though they may be performed under laboratory conditions. For the ordinary run of work the shop may do no more than set up and inject a few test molds and judge the patterns by visual inspections and by "how they feel in the fingers." There are no standard tests specifically designed to measure the properties of dispensable pattern materials. The standard tests of any kind for such materials are very few, and all of them were intended for finding the values when the materials were applied to electrical insulation or other quite different fields. A few are used occasionally in the precision investment casting field.

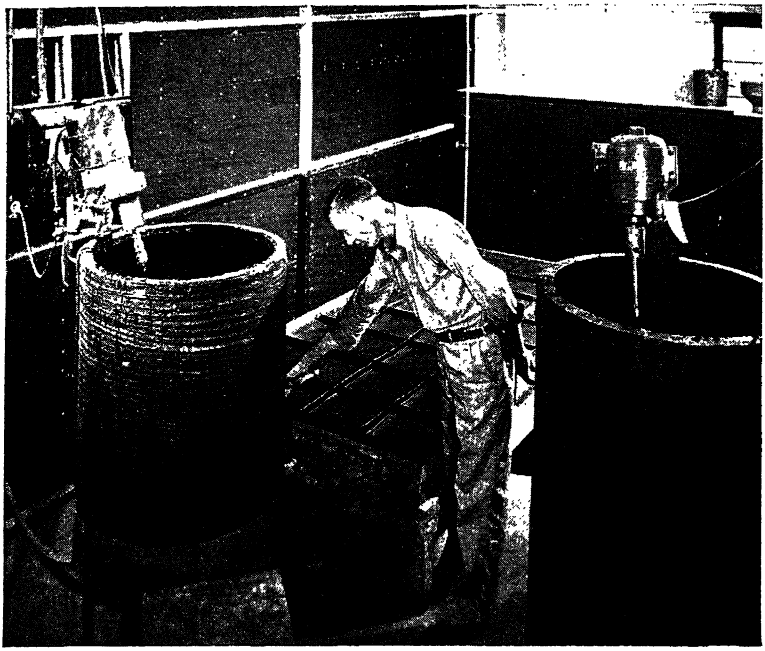


FIGURE 96. Blending pattern materials.

Viscosity. Viscosity, sometimes Saybolt Universal but more often Saybolt Furol, may be taken. The Saybolt Furol sometimes is preferred because it is more generally applicable to the measuring of viscosities at temperatures other than 70 degrees F. But the viscosity of a pattern material under gravity alone has no necessary relationship to what the material will do under much higher pressures and this is the information which the casting house needs to obtain.

Standard Penetrometer. This test is less generally known than the viscosity one. In this, as performed under standard conditions, a sample of the material is melted and poured into a standard sample tin where it is permitted to cool. The tin is placed in a pyrex transfer dish having a centering support, and this is placed in a constant-temperature water bath of the desired temperature for testing and is allowed to remain there for one hour. With enough water from the bath remaining in the dish to keep the tin covered, the dish is taken to the penetrometer so that it can be tested before the temperature of the sample has time to change.

The testing instrument and means of using it are described in American Society for Testing Materials designation D5–25.

It consists of a needle having a point of standard contours and dimensions, loaded with standard weight which usually is 300 grams, free to fall vertically when released, adjustable as to height before release, and equipped with a dial which shows how far it falls after release, the dial commonly being readable in hundredths of a centimeter. Various casting houses have their own ideas about needle point contours, weightings, and graduations on dials; the instruments in use are not all standard.

The sample is placed beneath the needle, the needle is adjusted so that it touches the surface, the needle is released and allowed to penetrate for a specified time, commonly one minute, and the dial reading is taken. This can give worth-while information about the softening points and the softened range of the material. But since there are more practical methods for finding out how the material will behave in the mold and in the injector, the main uses for the test are for inspecting ingredients which are to be blended and for checking patterns which have been injected.

In evaluating testing methods it must never be forgotten that the behavior of a pattern material when merely melted and poured into a mold is not necessarily the same as that of the same material after being injected at any pressure above 50 psi, and that the effects of pressure upon the material tend to increase with the pressure.

A pattern may be removed from a mold; therefore, placed immediately under the penetrometer, and tested. While the test is proceeding another pattern is injected and is allowed to be set aside until the test of the first one is completed, this time period being carefully observed. The second pattern is tested immediately, tests being made at thick and thin sections and at various of its areas. By testing several patterns with increasing increments of set-aside time the necessary duration of set-aside time may be estimated.

Further patterns may be raised slowly in temperature and their penetrometer readings taken at various points. This gives a measure from which the softened range at which the material no longer will be damaging to fragile members of the investment may be estimated. Ability to interpret this test depends upon knowledge of the pattern materials and experience in using it.

Dilation, Viscosity, Penetration Combination. One practical test which has, so far as is known, no recognition whatever by any scientific or engineering body is performed as follows.

A standard cylindrical sample of the material is forced to the bottom of a cylindrical glass tube, the material having been injected to a diameter slightly larger than the inside diameter of the tube, the tube being a standard gage glass such as is used on low-pressure steam boilers. A pattern or section broken off from a pattern is placed on the material. Bearing against this pattern is a steel rod having a ball point with an 0.20-inch radius. The rod has a scribe mark which can be compared to a standard steel scale mounted directly behind the tube and the movements of the rod thus observed. But the rod is held in vertical position by guides through which it slides freely, and the spring arm of a pantograph also bears against the top of the rod and exerts a slight pressure. The other end of the spring arm bears a pen which marks the line common to charts on an instrument chart.

The glass tube is surrounded by water and the water is gradually raised in temperature, the rate of increase being the same as that applied to investments at the melt out. As the investment material increases in temperature it expands and the expansion is registered by movements of the rod and is recorded by the pen. At some point in this rise the material will reach its softened range and the rod point will begin to sink into it. This point is plainly visible on the curve scribed by the pen. Later on, the material becomes soft enough to slide freely out of the tube and the rod drops down with

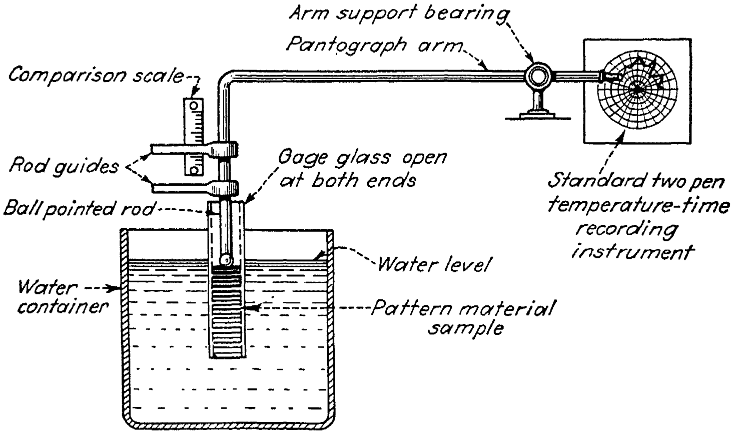


FIGURE 97. Schematic diagram of practical testing instrument.

it. The sliding usually is rather abrupt and plainly records itself on the chart.

The chart is on the face of an ordinary time-temperature measuring instrument. Therefore the time and temperature at which each significant movement of the rod took place is known.

Like all such instruments, this one must be used by an experienced operator. When correctly applied it can give information as to the expansion of the material before it becomes soft enough so that it is not likely to do damage to investment walls or fragile inserts, the real softening range, and the melting point at which the material may be recovered. It is important that the recovered material not be heated to any higher temperature than is necessary before removing it from the melt-out chamber. High temperature volatilizes some of its elements.

Practical Injector Test. A sample lot of the material is taken to the laboratory of one casting house and is placed in an injector. The injector is capable of pneumatic pressures up to 500 psi and hydraulic pressures up to 5,000 psi. The injector is heated to 115 degrees F, the lowest temperature at which this house injects, and pressure is increased on the material until it flows from the injector nozzle. This pressure is noted, is slightly increased, and a standard mold is injected. The pattern is carefully laid aside for observation of necessary seasoning time. The ejection from the mold is watched carefully for signs of the pattern sticking to the mold walls.

Temperature of the injector now is stepped up to 125 degrees F and the entire process repeated. This, of course, requires less pressure.

The process is repeated at 10-degree temperature increments until a temperature is found at which the material will inject satisfactorily at 50 psi. Then, if faulty, the material is temporarily rejected with instructions for reblending. But if accepted, the material is given an identifying lot number with written instructions as to the types of patterns for which it is suitable, the temperatures and pressures at which it should be injected, and the necessary set-aside time for each temperature and pressure. No injection pressure of over 3,500 psi is used at the production line, the higher pressures at the laboratory injector being for testing purposes only.

Practical Mold Test. At another house a special mold has been made. It consists of one upper and one lower member, both being so recessed that when fitted together into a mold, an interior chamber of circular shape, about 4 inches outside diameter by 0.250 inch high, is provided. The periphery of the chamber is interrupted at one point by a hole which extends to the outside of the mold and serves as an investment material gate.

Fitting inside this chamber and with no more than 0.0005-inch clearance at any point is a hardened and ground steel washer. The washer is not a perfect circle but is interrupted or cut through at an area which coincides with the pattern material gate of the mold, thus providing a continuous gate area to the interior of the washer.

The bore of the washer is marked off into four nearly equal segments. At each segment slots are cut into the wall of the washer. These slots are graduated by increments, the first being on the order of 0.002 inch, the second 0.005, and others increased by 0.005-inch increments until the last is 0.020 inch. The slots and increments at each sector are alike.

With the washer in place and the mold clamped shut, pattern material from a standard 100-psi injector is injected. The mold is opened, the pattern removed, and observation made as to which slots the material filled out and which it did not.

A material intended for patterns having fine members must fill out all slots but often will fill those opposite the gate but not the similar ones closer to the gate, in which case the material must be reblended for higher fluidity. But for patterns not having fine members this company often makes its molds with passages to permit the escape of air as the material enters the mold. Therefore the material must not fill out the smallest slots.

Ash and Residue Content Test. Pattern materials which are "100 per cent volatile, 100 per cent combustible" often are described, but rarely are encountered because of the impurities existing in most natural waxes. When castings must be of exceedingly fine detail and must be so clustered that not all of the molten pattern material can drain out, an ash and residue test may be needed. Both tests are laboratory matters and their techniques may be found in the literature. But as practical methods the following may be used:

(1) Place a sample of the material in an open crucible and place the crucible in an open and cold muffle furnace. Heat slowly, either igniting the sample when it reaches its fire point or allowing it to ignite spontaneously. Continue to raise the temperature until the temperature at which casting is to be done is reached. Hold the temperature at that point until constant weight of the crucible is attained. Then examine the crucible for residue.

(2) Invest a piece of the material in the ordinary way, let the investment set, cut the investment through in such manner that a chamber containing a substantial portion of the sample is open at one end like a crucible, then proceed as above.

Chemical Reaction between Pattern and Investment. Pattern residue and other troubles such as bad surfaces on castings often may be attributed to chemical reaction between the investment and the pattern material during the heat of the melt out. By examination of the chemical constituents of both materials, such a condition often can be predicted, and sometimes is foreseen by skilled sales engineers of pattern and investment supplies. When not anticipated it may result in dirty metal in the castings, in pits, and other troubles. The second method of testing for residue usually will find this trouble if it exists.

Test for Minimum Viscous Range. The "minimum viscous" behavior of pattern material in penetrating the pores of investments and retreating from the cavity surfaces is little understood by practical precision investment casting men although explanations might be found in the scientific literature on osmotic pressures. Its practical effects differ with investments and with casting problems. In several shops, if the pattern material retreats at least 0.125 inch from the cavity surfaces, it will cause no trouble, but at less distance air bubble troubles on the castings will be encountered, especially on interior or re-entrant angle surfaces and on undercuts.

This penetrative effect sometimes can be observed by the second method of testing for residue. But since the penetration may be caused or promoted by gas pressure as some elements of the pattern materials vaporize while others still are solid or liquid, many casting houses prefer to make an outright test of it.

Damaged patterns, or if necessary, good ones, are clustered and invested in the regular manner. The flask is melted out and burned out and brought to the casting temperature with others intended to be poured. It is set to one side and allowed to cool in air. It is then sawed into several sections, the cuts going straight across and through the pattern cavity areas. The area or areas to which the pattern material has retreated can be identified visually by the staining from the dyes which were mixed with the material.

If the pattern material has not retreated far enough, the usual remedy is to hold the flasks at casting temperature for a longer time period. Changing the pattern material is not known to affect this matter.

Test for Internal Strains. Internal strains within patterns can be the results of friction and viscous shear during the molding operation. See page 189.

Usually these strains have no bad effects. But they can cause warping of the pattern during the seasoning periods, with resultant inaccuracies, loss of surface detail and of contour fidelities. Or if invested in a material which is applied or which sets at temperatures materially above room temperature, the strains can release themselves with resultant losses of accuracy of the investment cavities.

One simple test for strains is a careful examination of the patterns. Strain lines may appear as striations plainly visible because they appear to be of different color tints than the main areas.

A more informative test is to lay a pattern on a piece of paper and carefully trace the pattern outline with a sharp pencil. With a fine wire held taut between the hands, the pattern is sliced into as long and flat pieces as its contours permit, thus obtaining thin, wide and flat layers. Each of these is laid on paper and the outlines of the layer carefully traced. In so far as is practical the outlines of each layer are compared to the tracing of the original pattern to see if warpage took place during the slicing operation. Each slice is allowed to remain in place for at least 8 hours and is checked against its tracing at suitable or convenient time intervals. Any serious warpage will be plainly evident. Also, any tendency of a slice to curl or bow will be evident.

Other samples are sliced in whatever directions seem to match the probable directions of stress, and are similarly handled. Warpage indicates the release of strain.

As a third test, entire patterns and slices of patterns are laid on a white asbestos sheet, traced, and the sheet carefully placed in a cold muffle furnace or in an oven, care being taken that the parts are properly in place in regard to their tracings. The furnace temperature, using recirculated air, is now raised to the temperature assumed by the investment when setting, and is held at that temperature for a somewhat longer time period than is usually necessary for the setting of an investment. Warpage will be plainly evident if it exists.

The most feasible cure for such warpage is injecting the patterns at a higher temperature, of the pattern material, the mold, or of both. Strains sometimes can be overcome by the use of a lubricant in the mold or the addition of a high lubricity ingredient to the pattern material.

Chapter 13

Clustering

The pattern cluster is the arrangement of dispensable patterns for simultaneous pouring of several castings. This arrangement must be complete as an operation before investing can begin.

The cluster sometimes is called the "sprue up," the "gate up," the "gang" and similar names. Shop jargon sometimes finds it convenient to identify types of clusters by objects which they resemble, such as "the Christmas tree" for a cluster which looks like a tree with bundles hung from its branches, and the "rake" for one which looks like a garden rake.

The clustering operation receives patterns almost as if they were finished materials to be assembled with the products of its own processes. Indeed, plastic patterns and some of those made of the more durable wax dispensable pattern materials sometimes are bought on contract from injection molding houses and delivered in boxes and barrels to the casting houses. The clustering in these instances is the beginning of the casting sequence.

Terminology. The cluster is melted out with the dispensable patterns. It is itself a dispensable pattern to join patterns. It takes its terminology from the function performed by the space which each member leaves after the melt out and burn out. This terminology could be called roughly approximate to that used in sand casting if it were not for the fact that sand casting foundrymen are by no means uniform in their terminologies. The terminology here is presented in the order in which the cluster is assembled. The same terminology is followed until the castings have been poured, the investment removed, and the castings cut off from the cluster.

Button or Base. A base may be made from rubber, plastic, metal or dispensable pattern material. It serves to hold the cluster upright so that it may be assembled and invested. The base may then be removed, but a remnant of it forms a down-gate passage through which the molten metal will be poured. The metal which solidifies in this area has the general shape of a large button and is called the "button."

Sprue. The sprue is the main passage from the button to the runners, or in some instances, to the castings themselves. In some shops if the main sprue is split into branches before being definitely bled off into runners, these branches are called "branch sprues." In other shops only one passage is called a sprue and all of its branches are runners.

Sprue Rod. This is a steel rod, tube, or other alloy part about which pattern material is poured to form the sprue or a large part of the sprue. It has two purposes. One is to reduce the amount of pattern material necessary for a heavy sprue. The other is to permit it to drop down the instant the pattern material softens and releases it, thus providing a free area into which the expanding material can expand and relieving the pressure of this expansion upon the investment.

Some shops prefer aluminum sprue rods because of the high thermal conductivity of that metal, the fact that the rod is lighter than steel and will remain in place for a longer time period and while doing so will conduct more heat to the sprue area and thus soften this area more rapidly than the pattern area.

Runners. Channels which run from sprues to gates.

Gates. The points or areas at which the runners meet the patterns.

Risers. Any areas from which molten metal feeds by gravity or by any other pressure into the pattern cavities which produce the actual castings. In centrifugal casting or pressure casting the entire sprue and runner areas act as risers. But risers may be special areas or cavities within the investment.

Multiple Gates. The castings may need either simultaneous or cyclically-timed feeding from several gates. This depends largely upon the alloys cast and the contours of the castings. Some alloy steels are difficult to cast soundly if the gates are more than 1.25 inches from any area or surface of the casting. When there are many cores or other intricate contours, the molten metal may be reluctant to flow around more than one or two of them. Additional gates then are needed. Each gate may have its own runner which leads to the sprue. Or, rarely, there may be more than one sprue in order to vary the riser effect at the different gates.

Simple Principles of Gating

The gate must be properly placed in regard to the contours, accuracies and other properties desired in the casting. This problem is not always critical. But in some castings long periods of trial and error must be spent before the proper gating can be determined.

Hot Spots. The gate must be so placed and contoured as to avoid the creation of hot spots and other stress risers at the gate area. Despite the fact that it is later to be ground off, the gate area is part of the casting. Hot spots occur at re-entrant angles ("interior angles") and at any area where the juncture of a thin section with a thick one is abrupt.

Hot spots may be inescapable in the designs of the castings. In these instances the gates must not be so placed as to compound the heat concentrations. Minor hot spots may be induced by the use of noncrushable investment cores. Many of these cores are higher in heat conducting abilities than are the main bodies of investment material.

Other minor hot spots may be caused by very close spacing of patterns within the investment, or by placing patterns close to the sprue. This close proximity of metal to metal often has a highly desirable annealing effect as the castings cool, and may be used to keep one area hot while another cools and thus to control the direction of progressive deposition. But it should not be allowed to cause or compound a hot spot.

Not Remelt. If the gating is such that metal will solidify in the vicinity of the gate, the cavity will be filled, the larger body of molten metal will remelt the originally solidified portion so that that portion has to resolidify, and the metallurgical condition of the casting may be predicted to be bad. This condition is especially to be avoided when there are two or more gates to the same casting. It has no known good points.

Thick Section Gating. In many instances it is best to gate to the thickest section. The thinner sections will cool and shrink first and while they do the thick section may be continuously fed from the sprue, the feeding thus preventing the condition in which the final shrinking of the thick section will not only make that section inaccurate but also pull the thin ones out of alignment.

Ideal Gating. The ideal gating is one in which all elements are so balanced that the entire casting cools and completes its shrinkage while the metal in the sprue and the runners is still molten, thus causing the worst of the shrink problems to be imposed upon the runners where they make no difference whatever.

Segregation vs Ideal Gating. When the melt contains metals which solidify at significantly different temperatures, the ones which solidify at the lowest temperatures tend to remain molten longest and therefore to segregate in the unsolidified portion of the casting until all of the metal solidifies.

More than one shop, aiming at ideal gating, has achieved it only to find that some of the most valuable ingredients of the alloy had segregated in the runners and sprues where they were of no benefit to the castings.

Metallurgical Soundness. Some of the largest casting houses, the ones which have spent the most money on research, have reported that the highest metallurgical soundness in terms of uniform distribution of all the metals in the alloy and of absence of shrink and porosity troubles is attained by the use of generous gates and small runners. The feeding of the casting is such that it continues as long as it is beneficial, after which the runners freeze before the gates. The runners thus impose shrinkage upon the gates but not upon the usable portions of the castings. And any segregation which may occur is within the usable castings.

Selective Area Tolerances. Unless sections are so proportioned that heavy areas as they cool can pull light ones out of shape, the first areas to solidify will be the most accurate as to dimensional tolerances and fidelities of contours. The exception to this is when shrink is restrained. But the non-crushable cores and other restraint members usually are rapid conductors of heat and therefore promoters of primary solidification in their areas.

Solidification normally will begin at the area farthest from the gate. Therefore, if selective area accuracy is desired, the gates may be placed at areas remote from the high accuracy ones.

Casting Method vs Gating. Precision investment castings are cast centrifugally, by direct pressure, and by gravity pouring. The first two methods force metal through runners more rapidly than does gravity alone, sprues and runners being of the same sizes. Therefore for the same rate of feeding, gravity casting needs larger sprues and runners.

Centrifugal casting often is intended to cause some elements of the alloy to deposit while others still are molten. When this is so, a force of phoresis is set up, causing different alloys and metallurgical conditions to exist at different areas of the castings. The gating must be such as to form straight enough lines with the sprues so that the phoresis takes place in the castings and not the sprues. See page 105.

Sometimes this phoresis effect is desired to be minimized. Its minimization is mostly a matter of controlling the centrifugal force at the casting operation. But this can be aided by so gating the pattern that the gate is at the area of greatest centrifugal force. The heavier elements of the alloy may be forced into the cavity first, but the lighter ones which follow them tend to re-alloy with them.

Pressure casting lacks the phoresis advantages and problems. But the metal entering the cavities does have the same hydrodynamic phenomena as were described for patterns. See page 188.

In fact, the hydrodynamic phenomena of metals are more bothersome than those of patterns, since the metal viscosities, temperatures, erosiveness and specific gravities are almost always higher. Changing the amount of pressure or changing the sizes of runners can aid in the control of hydrodynamic phenomena if they are bothersome. But changing the gate location so that no eddy currents exist in the immediate vicinity of the gate often is helpful.

Vacuum Casting vs Gating. In increasing numbers of instances vacuum is being applied to precision investment casting. There are three general results. The first is to remove air from the invested flask. The second can be to increase the pressure on the metal entering the flask. The third is to reduce air as a cause of bubbles on the surface of the casting and as a source of gas within the metal.

Invested flasks not under vacuum must be so gated and their runners and sprues so proportioned that metal enters the cavity in a direction from which it can most naturally drive the air into the investment pores, and with a speed no greater than that at which the air can be forced into the pores. When vacuum is applied some of these gating restrictions are eliminated.

Directional Strength. When centrifugally casting, directional strength may be imparted to precision investment castings. The strength arises from the fact that the heavier metals in the alloy tend to concentrate and to solidify first at the cavity areas which are furthest from the centrifugal axis and the metal therefore deposits in layers or striations from these areas back toward the button or down gate. Since any directional strength which exists will be parallel to, or at least generally lengthwise of, these striations. the directional strength will be greatest in the plane of centrifugal rotation and in a direction at right angles to the centrifugal radius. In short, using the Euclidian geometry concept that the radius generates a disc-shaped plane, the directional strength is parallel to that plane and at right angles to the radius if directional strength exists.

In some castings the value of this directional strength is high, especially if the castings have thin members which lie in the plane of directional strength. Very little design use has been made of this feature. The amounts and extents of directional strength are somewhat controllable by varying the speed of centrifugal rotation and the length of the centrifugal radius, thus varying the factors of centrifugal force and of inertia.

If directional strength is wanted, the patterns must be so gated and positioned that the striations will form in the desired directions. This is very largely a matter of trial and error. But once worked out it usually requires an accuracy of clustering which can be attained only by the use of fixtures.

The directional strength attainable does not seem to have been measured with such thoroughness that true estimates of its quantities can be given, but it does not approach that attainable in rolled or drawn alloys in which longitudinal strength sometimes is 500 per cent of transverse strength.

Shapes and Sizes of Gates

Gates may be simple terminals of runners with no change in the cross-sectional shape of the runner where it enters the casting. More often, gates are truncated cones, or truncated sections of other geometrical forms which if not truncated would terminate in apexes. The cone or other figure usually is in such a position that if not truncated its apex would be at some point in the runner. In short, the gate usually is an open mouth of which the runner is the throat, but the depth and shape and width of opening of that mouth is highly variable.

The possible variations are almost endless. They may easily run into the billions of combinations for any casting. If, for example, only 30 variations were possible, the number of their combinations would be 30 times 29 times 28 and so on until some number was multiplied by 2.

The most common variations are:

(1) Whether the shape is a truncated cone, a truncated sector of a disc (sometimes called a "fan"), or a simple continuation of the cross section of the runner.

(2) If a truncated cone or truncated pyramid or other shape, whether the plane of truncation as bounded by the lines of the gate is the same size and shape as the cross section of the runner, or is larger. And if larger, whether the center of the runner is a true continuation of the axis or center line of the gate or the two are off center to each other. And if the two are off center, whether they are parallel or at an angle to each other.

(3) Whether the truncated shape is all of the gate, or is channeled beyond one or more of its boundaries that face the casting, so that the gate becomes a primary gate with one or more secondary gates leading off from it.

(4) Whether the gate is an open mouth at all, or is one of the rare constricted-mouth types. When the metal is hot and fluid enough and the pressure high enough, the constricted-mouth type tends to increase the velocity with which the metal enters the casting cavity. Also the constricted mouth results in a necked-down area at the runner, often making it possible to break the castings from the clusters by merely shot-blasting the clusters, the shot-blasting also serving to remove the final traces of investment.

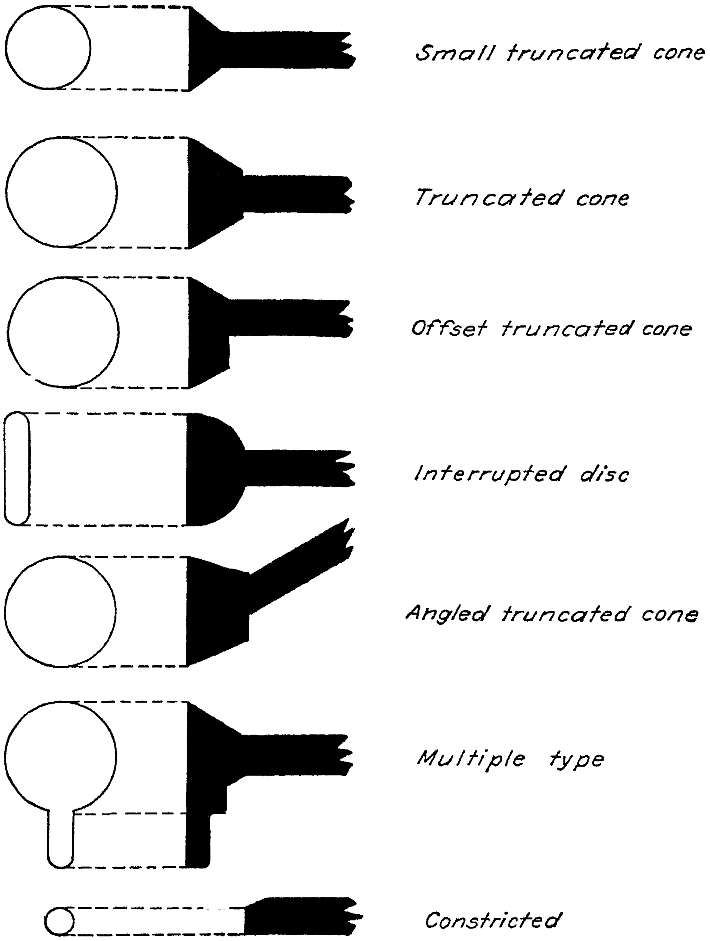


FIGURE 98. Some of the more common types of gates.

Truncated Disc Sector Types. A truncated disc sector is the shape of a piece of pie with the point cut off where the point otherwise would enter and plug the runner. The height or thickness of the sector may be governed by the thickness of the casting section to which the gating is done. Otherwise, dependent upon the pressure and fluidity and hence the velocity of the entering metal, such a gate tends to emit fan-shaped streams of molten metal.

These somewhat flat and wide streams can, if they cool rapidly enough, appear as striations in the casting and can impart directional strength. The method of casting, whether centrifugal or direct pressure, makes a difference to this striating effect. If centrifugal, and the streams are flatwise to the centrifugal force, the striating effect may be increased somewhat, although as is generally the case with directional strengths in castings, the full effects do not seem to have been scientifically evaluated.

The purpose of the truncated disc may be to flow the metal past a fragile insert or an obstacle of any other kind within the cavity so that that obstacle neither is broken by the force of the entering metal nor is allowed to act as a chill spot which will cool the first metal to enter and then allow that metal to be remelted by the metal which follows.

Truncated Cone and Pyramid Types. A truncated shape of wider base than that of a disc (and thousands of shapes are possible) results in a slowing down of the metal as it leaves the runner. This slowing down is accompanied by expanding of the molten stream, and expansion tends to cool any liquid. Since the stream is flowing through channels in an investment which is cooler than itself, the net cooling effects can be highly varied.

Expansion is accompanied by loss of velocity. Consequently the gate controls velocity and direction of feeding to the cavity. The air must be pushed out of the cavity with the hot metal acting as the plunger in a cylinder. But the velocity and rate of cooling must not be such that the freezing alloy will tend to "bridge over" small cavities and prevent their being filled, or to promote directional solidification in such wise as to overspeed it and result in over-segregation of the highest freezing-point ingredients of the alloy.

The gate also can direct the stream of metal in such wise that cores and inserts do not become chill areas and are not fractured by the metal, but are surrounded almost simultaneously at all of their surfaces. This is especially important when the inserts are fragile.

The metal in its flow will follow the laws of hydrodynamics as discussed for injection of patterns. See page 188.

When the metal is to be cast at the lowest possible temperature in order to obtain the least shrink and the highest accuracy, the directing of flow is difficult. If the flow is directed at a crushable core or other fragile member, the chances of fracturing that member are highest. And if the direction is such that the stream travels around the surface of the cavity so as to surround the fragile part, there may be enough cooling action to produce a mild weld line where the leading edge of the stream meets the incoming metal at the gate.

Gate sizes, positions and shapes are largely matters of trial and error, even in the casting houses which have handled thousands of problems. Gating is a craft, an application of instincts and experience as well as of knowledge, it is not even an art or a skill, much less a science. In one example a truncated cone-type of gate was 0.125-inch deep as measured from the face of the casting. Thinking to improve the precision which already was plus or minus 0.001 inch per inch, the casting house made the gate 0.250-inch deep. With the deeper gate the precision could not be held even to plus or minus 0.004 inch per inch.

Risers

Risers are reservoirs of molten metal intended to feed the casting as it shrinks and thus to maintain dimensional accuracy and contoural fidelity by filling up the spaces which otherwise would be created by shrinkage. Very rarely does all of the riser feed into the casting. Therefore some of the riser remains as waste metal which must be cut away. And since the riser is to be remelted or discarded, efforts are made to cause any air or gases which will be given off at the casting to penetrate and do their damage at the riser rather than at the casting. The riser also may be arranged to be the last area to shrink and thus to absorb many of the shrinkage problems.

Blind risers, that is, risers not open to the surface of the investment, are the most usual ones in precision investment casting. Open risers are rare.

Many casting houses report that they never use any risers at all, except that in either centrifugal or pressure casting the sprue metal is forced toward the casting cavities and so is a riser. But nearly all houses report that if any castings at all show signs of air damage or inordinate shrinkage they will be the ones at the upper area of the invested flask, thus suggesting that these castings have acted as risers and have fed the ones below them. The air which is forced from the cavities into the investment usually follows the interior areas of the investment walls and seeks a path of escape. This air, having been heated by the incoming metal to a temperature which usually is materially higher than that of the investment, tends to travel in an upward direction within the investment walls. Often this air finds its easiest path of escape in the topmost cavities. In addition, the bottom cavities tend to be filled first and therefore air under compression may be forced into the top ones, causing the entering metal to attempt to force more air from the top cavities than is possible. By both of these means the topmost cavities may obtain excess air and become risers.

Risers therefore often are deliberately created. If so, their pattern materials may be the cheapest obtainable, since dimensional accuracies of risers are of no consequence. The cluster members must be structurally capable of bearing the weights of the riser sections as well as those of the patterns. And the passages from the risers must be gated to the castings, the gating problems being the same as those of the runners.

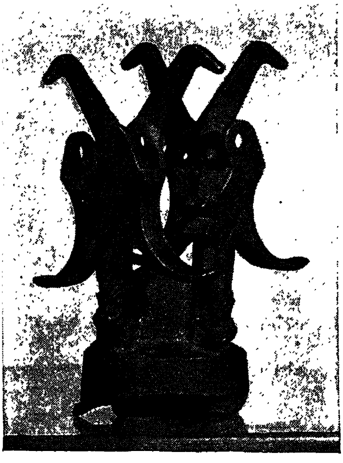


FIGURE 99. Nearly all of the pattern material can melt out through the sprues.

Positions of Patterns Relative to Sprue Axis

For Melt Out. In order for the pattern material to run out when melted, the invested flask will be placed in the melt-out oven in such a position that the button is downward. If the gates, runners and pattern positions are such that the entire load of dispensable material can drain out, the salvage of valuable material will be highest, the amount which will have to be volatilized and burned will be least, and the amount which will retreat into the investment will be reduced.

Therefore, if no other considerations prevent it, the flow out should be made complete. But this rarely is practical.

For Blind Holes and Undercuts. The air must be evacuated from most investments before they are permitted to set up. When evacuating, the sprue normally leads in a downward direction since the cluster is standing on its base. If practical to avoid this, blind holes and undercuts must not be in such downward positions that they will entrap air and prevent the vacuum or the vibration from drawing it out of the investment. The presence of these blind holes has been known to require such inconvenient positionings of patterns as to reduce by 50 per cent the number which could be clustered within a single investment, thus increasing costs per casting by as much as 25 per cent.

The entrapped air not only is bad for the investment, but can prevent some investments from entering the blind hole core areas and thus can defeat the purposes of those cores. There are several resources for handling this problem. Among them are:

(1) Investment materials of such high wetting-out abilities that they will fill the blind holes and displace the air.

(2) Precoat investments which will fill the blind hole areas while coating the patterns, allowing the main body of investment to be applied as if the holes did not exist.

(3) Investment cores either crushable or shrink restraining, used as inserts in the molds, remaining in the patterns, acting as cores for the blind holes but removing those holes as investment problems.

(4) Inserting the cluster in the flask and placing this assembly within a vacuum chamber which also contains the investment material. The investment material is in a container and may be poured by mechanical means without releasing the vacuum. The air is evacuated from the chamber, the investment is poured, and in the absence of air there can be no air pocket troubles. This method is rare but is highly feasible.

In a great many instances the easiest and most economical method is to position the patterns so that their pockets can entrap no air.

Thick Sections. Thick sections tend to round out on their flat surfaces, or to "belly." There are resources to prevent this, but clustering methods also can help.

If those thick sections can be so placed that their flat sides are generally radial to the sprue axis and their thin edges are toward the outer surface of the invested flask, directional solidification should be from the outer surface inward, the flat surfaces will tend to build and shrink by increments, and the bellying problem will be reduced.

Intermingling. Clustering for highest economy often resembles the arranging of goods within a shipping package. Smaller parts which are to be cast of the same alloy may be placed between some areas of larger ones. Where large parts have thick sections continuous with thin ones, if the problems of gating permit, the positions of thick and thin sections may be alternated, thus getting more castings out of the same invested flask.

Connecting. When one casting consists of a thick section and another of a thin one, the two often can be cast as members of each other and cut apart after removal from the investment. A runner may be needed between them.

Flask Shapes and Sizes

Although most casting houses prefer to use a few standard shapes and sizes of flasks, there are few limitations on these factors. Flasks can be round, square, oblong, or hexagon-contoured and can have interior and exterior fins to solve problems of heat transmission.

Sizes are limited only by such practical considerations as the charges of melting furnaces. There is no point in having a larger invested flask than the shop is able to pour. Whatever the shape and size of flask, the cluster must conform with it. If the flask is round, the cluster usually will be a "tree" shape. For a square or rectangular flask the cluster is likely to be a "comb." But the flask shape often is selected to be economical for the cluster rather than the cluster for the flask.

Small Flasks. Flasks holding from a few ounces to less than two pounds of metal may be preferred for tiny castings. The weight of excess metal poured into sprues, runners and risers increases rapidly in proportion to the size of the flask since this waste weight must be sufficient to feed the topmost cavities. Also, the problems of proportioning the various levels of runners and gates may increase with flask size.

For larger castings, larger flasks are more economical.

Spacing of Patterns. If patterns are of the general shapes of cubes, it is apparent that if "treed up" in round flasks their spacing will be closer at the area closest to the sprue than at the outward area; they will be arranged as if each were on a spoke of a wheel of which the sprue was the axis. There is a minimum limit of about 0.125 inch of investment material which should be between any two cavities at any point. Therefore these cubes would be 0.125 inch apart at their inner surfaces but would have thick and wasteful areas of investment between them at their outer ends.

If the same patterns were arranged in straight-sided flask, they could be evenly spaced and parallel, thus getting more castings from the same invested flask cost.

Other shapes, of course, may more conveniently be arranged within circular flasks. The convenience of spacing of patterns often dictates the shapes of the cluster and of the flask.

Heat-Treatment within Invested Flasks

For Slow Cooling. Castings may be desired to cool slowly and uniformly after solidifying. The cluster then should be so arranged that all of the castings are as close to the sprue as gating and other considerations permit in order that the heat emitted by the sprue will be transferred to the castings. The castings also should be spaced as close together and as uniformly as the 0.125-inch minimum thickness of investment wall permits, so that the casting which cools first will tend to pick up heat from its neighbors. And the investment wall outside of the castings should be at least 0.50 inch thick.

Contours of the castings and consequent difficulties of obtaining uniform spacing usually present the greatest problem of uniform and slow cooling. The meeting of this problem may dictate the shape of the cluster and the flask.

For Rapid Cooling. Where rapid cooling and positive control of directional deposition are desired, the castings may be placed as far from the sprue as practical, with the minimum of 0.125-inch thickness of investment at their outer dimensions, and with spacing between them as wide as practical in order to secure the full insulating value of the investment. Since the flask is of metal and is a more rapid conductor of heat than is the investment, with only one-eighth inch of investment between flask and castings, the flask will act as a chill. The areas of the castings desired to be solidified first can, if gating permits, be closest to the flask.

This procedure calls for a different size and shape of cluster and flask than does slow cooling.

Flask Material. Flasks commonly are made of low scaling grades of stainless steels because of high durability of these alloys. Where slow cooling of castings is needed, the heat sluggishness of stainless steel is desirable. But where rapid and selective area cooling are desired, a flask alloy higher in heat conductivity is better.

Controlled atmospheres in melt-out chambers can reduce the scale problem. It is true that scale is largely an oxide and that oxygen is likely to be present. But control of moisture in the air which enters the chamber will reduce the scaling of the flask. The air should be dry.

Flasks high in heat conductivities can be protected by metallizing them with Nichrome and other alloys, as is done with carburizing pots.

Investment Pouring vs Clusters. Investment materials may be applied in two coats, three coats or one coat. If in two or three coats the first coats are dipped, sprayed or painted on the patterns. The clusters then must be arranged so that this operation is practical.

The flask usually is the full effective height of the investment and therefore at least 0.50 inch above the top of the cluster when the cluster is within it. For either one-coat investments or for the final and heaviest coat, if more than one coat is used, a fairly thick and viscous investment material must be poured into the flask to fill it. The cluster must have such shape and size that it is possible to pour this material without rupturing the cluster, or else the cluster must have sufficient mechanical strength to withstand the pouring. The pouring may be a skilled operation.

Cluster Shapes for Cleaning Out and Cutting Off

Cleaning Out. After the casting process the investments must be removed from the flasks without damaging the flasks. There are various methods for doing this. One is to drop the entire hot flask with its solidified contents into cold water. The investment usually will break and sometimes will turn to powder. The hot castings then are quickly cooled to room temperature.

This method may have a bad thermal shock effect on some alloys. In these cases the entire mass is allowed to cool, then is mounted in a hydraulic press and the investment pushed out of the flask. If this is to be done, a standard size and shape of flask, and a cluster to fit it, may be preferred in order to save the costs of fixtures at the press.

With the investment free of the flask a pneumatic hammer may be applied to the sprue button. This usually will shatter the brittle investment. But some of the investment will cling to the cluster. The remainder must be removed by grit-blasting or by steam or similar methods. The shape of the cluster and the tightness with which the castings are packed together will influence the ease with which this final cleaning may be done, and therefore the amount of grit-blast finish which is applied to various surfaces of the castings. When this effect is damaging, the arrangement of the cluster may have to be modified accordingly.

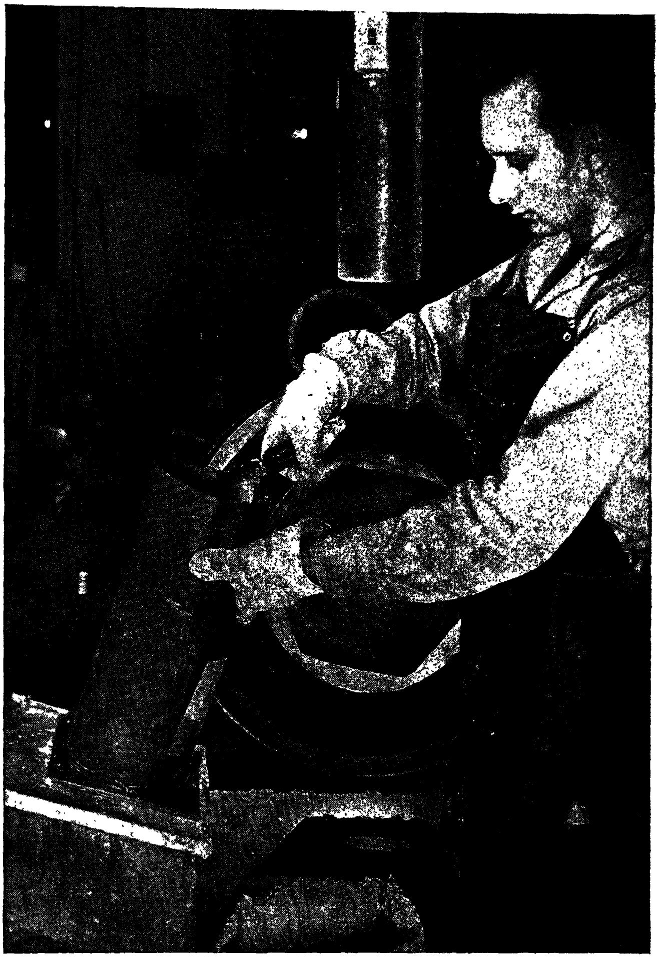


FIGURE 100. Pouring the investment material down beside, around, and then over the cluster.

Cutting Off. The patterns must be cut off from the runners or from their gates. If the cluster can be so arranged that a friction saw can run in a straight line and sever a few runners before the assembly has to be turned for another passage of the saw, this cutting-off operation is simple and inexpensive. But if the cluster is such that the runners must be severed one at a time with an abrasive wheel, the operation is costlier. This consideration alone may dictate the shape of the cluster and of the flask which fits it.

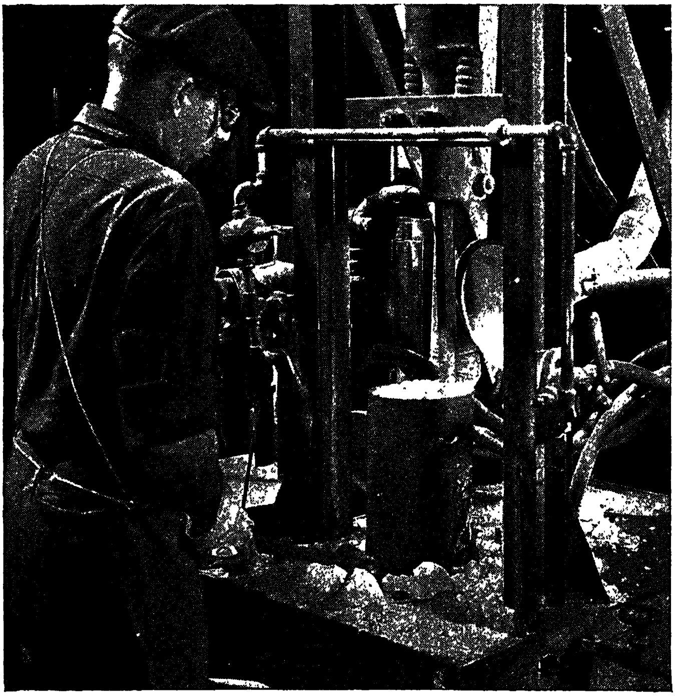


Figure 101. Breaking out.

Alloy Salvageabilities vs Clustering

If the cast alloys are readily remeltable, liberties may be taken with sizes of sprues, lengths of runners and other factors which lead to excess metal in the invested flask. Castings also may be given preliminary inspections while still attached to their runners, in order to avoid cutting off any which should be remelted.

Other alloy scrap is remeltable only after careful re-alloying. Some metals such as aluminums are inferior if remelted and recast and as such are known as "secondary metals." In these instances every possible design stratagem must be used to avoid excess waste metal in the cluster. The factors of ease of cleaning out, of inspecting before cutting off, and of cutting off, may be ignored in the cluster design if they interfere in any way with keeping down the excess metal within the invested flask.

Manufacturing the Cluster

The sprue usually is a straight shaft. There is no sure way of calculating its proper diameter except to treat it as the interior of a pipe which is to transmit a given amount of liquid metal within a given time.

FIGURE 102. Even in the best shops clustering is high in employment of manual labor.

If there is no problem of the remeltability of the waste metal, the size calculation will make generous allowance for the fact that some of the alloy will freeze to the sprue walls and reduce the diameter of the pipe, since the investment is of lower temperature than the molten alloy. But if the alloy is difficult to remelt or loses some of its qualities in remelting, the size of the pipe is calculated to be as small as possible.

Gravity or low pressure casting generally needs larger sprue diameters than does centrifugal or high pressure casting. Alloys sluggish in their flows need larger diameters than highly fluid ones. Alloys poured at temperatures close to their mushy ranges need larger sprue diameters.

When slow cooling of the castings within the flasks is desired, the sprue is made larger in order to supply a greater bank of heat. When rapid cooling is wanted, or the entire flask is to be quenched for abrupt cooling, the sprue is made smaller.

Many shops have arrived at sprues which meet average conditions, and have adopted standard sprue molds into which to inject them. The making of a sprue thus is an injection operation and may be done in a mold made of any convenient materials. Reclaimed dispensable pattern material almost always is used. If a sprue rod is to be used, provision must be made for enclosing it as an insert within the pattern. The molding may include fastening the sprue to the base. Some care must be taken with keeping the parting line down, otherwise it may be at an inconvenient position for assembling the cluster. Many shops use metal tubing as sprue molds, thus eliminating the parting line.

Runner Molding. Runners often may be as standard as the sprues. The principles for determining sizes are the same. But runners may need to be curved in various ways in order to conform with the design needs of the cluster. The curves or bends should be no more sharp or abrupt than necessary. And where a sharp bend is needed, the runner size should be increased somewhat.

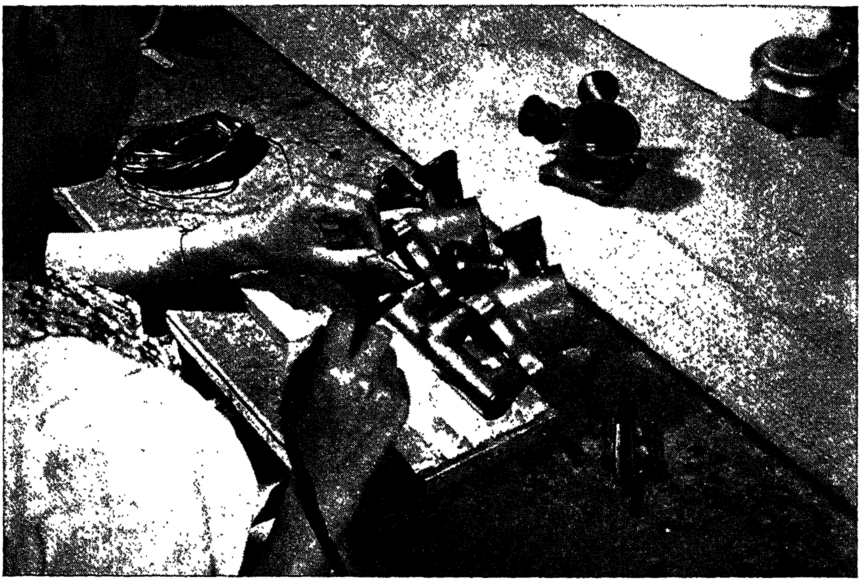


FIGURE 103. The gates are on the runners; there are two gates for each pattern; attachment tool is a thermostat-controlled soldering iron.

Gate on Runner or on Pattern? If the sprue and runner is not to be molded integrally with the pattern, or the runner is not to be so molded, the gate section must be molded either as part of the pattern or as part of the runner.

The choice is largely one of convenience, but product design considerations are important. If the gate area is molded on the pattern, the tool marks made when assembling the cluster will appear on the gate and will be removed with it from the casting. But if the gate is wholly molded on the runner, the tool marks must appear on the casting. They will make no difference if on a surface which is to be machined or ground.

A third choice is to have part of the gate section on each member, thus getting rid of tool marks on the casting.

If the gate section is on the pattern, it must be as accurate as the remainder of the pattern, and this can lead to high values in the accuracy of the gating. If the gate is on the runner it may require more than usual accuracy in the molding of the runner.

Hand Methods for Assembling Clusters. Members of the cluster may be attached to each other by moistening the mating surfaces with a solvent such as acetone or carbon tetrachloride, by the use of common glue or of airplane cement, by moistening the mating surfaces with molten wax and then quickly pressing them together, with some materials in noncritical surfaces of heavy section thicknesses by simply pressing them together, and by the use of hot tools.

The hot tool method is generally *preferred.* Tools may be spatulas, dental tools, or any appropriate shapes. They should have wooden or other heat insulating handles. The heated end of the tool is placed against the mating surfaces, and the surfaces are immediately pressed together.

The temperature of the working surface of the tool should be no less than 225 nor greater than 250 degrees F. Many casting houses use electrical soldering irons equipped with special thermostats. Another method is to use an electrical hot plate upon which the tool is laid when not in use. The hot plate should be thermostat controlled. Open gas flames into which the point of the tool may be thrust are used sometimes, but are not to be encouraged since they lead to overheating of the tool.

The soldering irons are advantageous for some work because the operator need never lay them down and thus, under some circumstances, can work faster. The hot plates permit the use of lighter weight tools which are less fatiguing to the operator, and also permit a selection of tools having different shank curvatures and face shapes to be always ready for use. Choice between these methods is an ordinary matter of time and motion study for the task in question.

Molten wax, if used, is almost certain to be splashed or spilled onto the hands and arms of the operators. It is generally believed that at temperatures up to 175 degrees F this will do no more than sting and will not cause serious burns, but before assuming this, the plant safety man should try splashing some on his bare elbow or some skin area other than his hands. A very much lower melting temperature is better.

Molten wax almost always leaves a ridge or uneven section where it is applied. This does no harm if the ridge appears at a point where the casting is to be machined or the metal is to be discarded.

The application of the wax may be by spatulas, pine or other wood sticks, small paint brushes or by pouring from the spout of a can. The wooden tools often are preferred for their light weights and low thermal conductivities; they do not cool the wax as much as will a metal tool, and with the wax remaining fluid, the operator has more time in which to take more care with her work.

Time and motion studies show the molten wax method to be the most rapid for some cluster assemblies.

Fixture Methods. Offhand methods of assembling clusters can have serious faults. They are high in labor costs, introduce the human element into an operation which needs great care and high accuracy, limit the closeness with which patterns may be spaced to the spaces within which human fingers may work, and sometimes slow down the entire production line.

Fixtures may be made of wood or of any materials to which hot wax will not readily cling. Very rarely need their costs be high. Entire assemblies may be laid in fixtures and then the cluster members joined by the use of hot tools, of molten wax, or of both. Since the members of fixtures are readily separable, their operating speeds can be high without any sacrifices of precision.

In one example the patterns were to be gated from both ends. Runner members were so molded that the gates extended from their main sections like the teeth of a rake. The patterns were laid or ranked in recesses which fitted their contours, the recesses being in the surface of a flat tray. The runners were laid in similar recesses so positioned that the gates would clear the pattern areas by about 0.020 inch, this accuracy being noncritical. The operator poured molten wax into each 0.020-inch interstice, then cleaned up the junction point with a hot tool. The tray then was allowed to rest until the molten wax had fully cooled. In the meantime the operator worked on another tray. The time per cluster by offhand methods was 28 minutes. The time by fixture methods was 2.15 minutes. The cost of the fixture was less than $20.00.

In another example the runners are molded with the patterns. The free ends of the runners must be attached to the sprue. The sprue is mounted in its base to hold it in fixed position. The fixture consists of separable sections which when assembled will clear the sprue by about 0.030 inch. Each section contains a channel into which a runner may be laid. The fixture is in sections which are separable lengthwise, but only its top members contain the runner channels. The fixture is assembled about the sprue, the topmost runners are laid in the channels; a hot tool is used to attach these runners to the sprue. The bottom member of the fixture is removed, allowing the channels to "slide down one row"; the fixture is turned so that the runners will not be directly in line with each other along the longitudinal dimension of the sprue; the operation is repeated. Four rows of runners are thus placed along the sprue and the fixture is removed, the resultant cluster being a tree shape. Time for assembling this cluster by offhand methods was one hour; time by fixture methods 12 minutes. Only 12 patterns were placed in the cluster by hand methods, but 28 may be placed with the fixture. Because of the closeness of the casting cavities and the bulk of metal within the invested flask, the metallurgical condition of the castings is greatly improved. Cost of the fixture was less than $60.00.

Fixtures vs Cluster Design. The advantages of using fixtures for cluster assembling often dictate the size and shape of the cluster. Rectangular clusters and flasks generally are easier to work out into fixture assembly methods. But many round or "tree" clusters are worked out first as angled or rectangular subassemblies and then finally assembled into the tree forms.

Standard Fixtures. Many casting houses make wide use of their own standard sprues, runners and fixtures. The detailing of a cluster assembly thus is made very easy.

Assembly Molding. An entire assembly of patterns and their gates and runner or runners, or of runners and patterns and of sprue or sprue sections, may be molded at the original pattern injection.

In one example a tree type of assembly was wanted. There would be five runners at each row around the tree and one pattern at the end of each runner. It was found that by offhand assembly methods only three runners could be attached and only three rows of runners, making nine patterns per invested flask.

The sprue was molded in sections, the sections being identical, and each section terminating in a row of runners and patterns, the complete section being injected as a unit. The sections were assembled by pressing the bottom surface of each sprue part upon the top surface of another, care being taken not to get the runners aligned with each other longitudinal to the sprue surface. By this method five runners could be used to a row and six rows per completed assembly, a total of 30 patterns.

Time for assembling nine patterns per invested flask had been 1 hour 20 minutes. Time for assembling 30 patterns per invested flask was 2 minutes and 30 seconds. Added cost for the larger capacity mold equipment was about $500.00. When all of the savings at the clustering, investing, casting and inspecting were totalled, it was estimated that this mold cost was repaid within the first five days of operation.

Cleaning the Cluster. When the casting surface is desired to be fine, and when a double- or triple-coat method of investing is to be used, the cluster should be cleaned as the final operation upon it. Any degreasing agent which is not a quick solvent of the pattern material may be used. Alcohol, acetone, various commercial degreasers are in use. The type of degreaser may depend upon the mold lubricant used at the pattern injection.

Chapter 14

Investing

The operation of investing the cluster may be considered to be completed only when the invested flask is at the casting machine and ready to be poured. Every production step between the placing of the cluster in the flask and the final heating or cooling of the invested flask for casting affects the selecting and handling of investment materials.

The production cycle of investing is highly variable in accordance with the investment materials used and the alloys to be cast and the metallurgical results wanted. In brief, the cycle is:

(1) Weigh out the materials.
(2) Dry mix the materials.
(3) Place the cluster within the flask.

At this point a wide variety of steps may be taken. Investment materials may be applied in one coat, two coats or more than two coats. Their application by two or more coat methods may involve spraying, dipping, painting and other methods which will be described later in this text. There may be varied mixing and drying and setting-up methods also. The brief description of the cycle proceeds:

(4) Wet mix the ingredients.
(5) Apply first coatings (if any).
(6) Pour mixed materials into flask.
(7) Eliminate air by vibration or by vacuuming. Either or both may be done.
(8) Allow to set, much as Portland cement sets up and hardens.
(9) Melt out, for preliminary evacuation of pattern material.
(10) Vaporize out or burn out remainder of pattern material.
(11) Bring to casting temperature.

Materials and Methods

Investment materials consist primarily of refractories, vehicles and binders. In addition they may contain hardeners, wetting out agents, water repellants, and agents intended to control the decarburization and other surface conditions of the castings. Other additives control the expansion and other characteristics of the investments themselves.

Before deciding upon what investment to use and how to use it, the casting house must consider many factors. The factors can exist in so many combinations that some houses use eight or more investment formulas to meet different problems.

Proprietary Brands. There are a great many proprietary brands of investment materials. Some are sold only to licensees under various precision investment casting patents. But the great majority are sold on the open market and are backed by high-grade sales and application engineering. The sales engineering as a consultant service on other casting problems as well as those of investments can be worth more than the materials cost.

Individual Formulas. Many casting houses compound some of their own investment materials and keep their formulas secret. The secrecy may be protective to a genuine trade advantage over competitors. But more often the formula fits the operating procedures of that house alone and would be useless to competitors, the secrecy then being imposed because explaining the reasons for using the formula would take too much time and trouble.

Costs of Investments. Investment materials are sold by the pound but used by the cubic inch. Their real costs are the costs per cubic inch or other unit volume within the flasks. They vary widely in specific gravities and therefore in the number of pounds per filled flask or per other unit volume. They have varying abilities to be mixed with low cost fillers, and this also affects the cost per unit volume. As an index of procurement value, costs per pound mean nothing until translated into costs per invested flask.

Temperature of Molten Alloy. Plaster of Paris can be used as an investment material if the pouring temperature of the cast alloy is 2000 degrees F or less. Usually only 20 to 50 per cent of plaster is used, the remainder of the investment being lower cost refractory filler material. The resulting investment can be used in a single coat, is highly fluid and will follow contours well and fill up undercuts and blind holes, is easy to handle when investing and to remove after casting.

At about 1300 degrees F this material begins to break down. The breakdown is less than 1 per cent up to some 1500 degrees F, and has no significant effect upon the strength of the investment. At

1700 degrees F the breakdown is rapid enough to make some clusters impractical for investing. At 2000 degrees F the breakdown is rapid enough so that this material rarely is used at any higher temperatures.

The accepted dividing line between a low- and a high-temperature investment material has become 2000 degrees F of molten temperature of the alloy to be cast.

The 2000-degree limitation sometimes can be exceeded. Plaster of Paris is calcium sulfate. If mixed with reducing agents, and if the castings are to be very small so that they do not have very much heat capacity, the plaster sometimes can be used with alloy melting temperatures as high as 2300 degrees F.

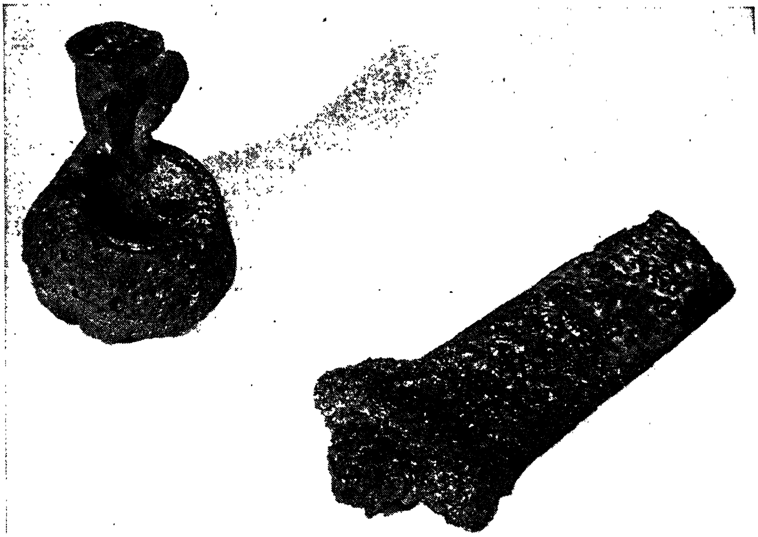


FIGURE 104. The "casting" on the left shows what happens when dirt gets into an investment material. The casting on the right is a steel piece which was cast into a plaster of Paris investment.

Chemical Effects upon Alloys. At higher temperatures calcium sulfate breaks down into various oxides of calcium and of sulfur. Various of these chemical compounds can have bad effects upon alloys, creating gas porosities, ruining surfaces of castings, even turning steels into structures which look like sponges. This is an additional reason why plaster of Paris rarely is used as an investment for steel or for any other alloy having a molten pouring range of over 2000 degrees F.

Oxides of sodium, silicon, zirconium and manganese can have slagging effects upon some alloys. The effects appear to be worst when mixtures of oxides are used. Investments materials have been known to fuse or "burn in" with the surfaces of castings.

Many casting houses divide their alloys into "high reactance" and "low reactance" types and will not use some ingredients in investments intended for the high reactance types. For example, one house will not use phosphates in investments for high chemical reactance-low carbon steels, but will use them for the much lower reactance stainless steels.

There seems to be no satisfactory body of knowledge on this subject. Refractories generally have been developed with the idea of high durabilities when subjected to large bodies of molten metal and not for absolute lack of reaction with the surfaces of very small bodies of molten metal. Refractories for precision investment casting are under intensive research at the present minute. Until that research has progressed a little farther, the subject will be one of trial and error for the casting houses, with the widest knowledge being in the hands of the manufacturers of proprietary brands of investment materials.

Silicas, zirconias, magnesias and aluminas are generally considered satisfactory for all alloys. The most commonly used forms are sand, mellite, sillimanite and bauxite.

Setting Up. Setting up of the investment material is similar as an operation to the pouring and setting up of ordinary concrete. The materials are poured in fluid form and must have time to set up or become solid.

Some investment materials set up in one stage, others require two or more. In the one-stage method, the setting up is at room temperature after which the flask can, if desired, be placed directly in an oven at a temperature well above the boiling point of water for rapid melt out and heat up. In the two-stage method the investment first sets at room temperature, then must be placed in an oven at not over 210 degrees F for a secondary setting up. In three- or more-stage setting-up types the investment may need dryings beneath hoods, or other operations.

If the invested flask is to be heated very slowly and carefully for the recovery of the dispensable pattern material, the one-stage investment has no advantage in being one stage. But the one-stage investment may be capable of two-stage use and have other advantages. Plaster of Paris, for example, can be used for either one- or two-stage techniques, and has advantages for many of the nonferrous alloys.

The exact timing of the setting up may be critical or noncritical. For an alloy which was intricate to cast, a casting house used plaster of Paris inhibited with reducing agents. The investment was successful but was subject to hygroscopic expansion. Stop-watch timing had to be used in order to get the invested flasks into the oven when they had set, but before the expansion could eliminate all precision. In any but a special operation this timing would have been a nuisance.

One shop changed its binder to save money. The previous binder had set up in 24 hours. The new one needed 48 to 72 hours. This threw the production scheduling completely out of line.

Production scheduling is an important factor. One of the largest casting houses uses no investment material which will set up in less than ten hours or be damaged by standing as long as 72 hours after setting up. This house uses a long and gentle melt out. Invested flasks move into the melt-out oven in dollies, and spend at least 7 hours there. The first 6 hours of setting-up time are spent before the flasks are placed on the dollies, the time at room temperature being extendable to 68 hours if the production line is not moving rapidly. Four hours are needed for melt out before the burn out and the heating up. The result of having a constant storage of invested flasks ready for the heating-up cycles is that the casting equipment always finds flasks ready when it is ready to pour them. Delay at the casting machines can mean spoiled alloys.

Because of the slow setting time this house always can have a two hours' supply of dry mixed investment and a one hour's supply of wet mixed ready to go to work. This smoothens the production line, allows the operators to take more time with pouring intricate flasks and less time with simple ones.

Another house uses an investment high in strength and in thermal conductivity, but quick in setting time. This material must be wet mixed, poured, vacuumed and vibrated as rapidly as the operators can work. It sets up in five minutes and is too hard for vacuuming long before that time. Many spoiled investment materials and unsatisfactory castings have been traced to failures to get the vacuuming done in time. But the metallurgical advantages plus the short time in which it is possible to turn a pattern cluster into a cluster of castings are considered to be more than compensatory.

Setting-up time sometimes can be altered at the mixing of the materials, a thorough wet mixing speeding the setup, and a less thorough one slowing it down. Setting up also can be varied by changing the vehicle in some investments, alcohol causing faster setting up than water, and mixtures of alcohol and water or of other solvents which are miscible with water giving intermediate setting-up times.

Plaster of Paris investments usually set up within 20 minutes of pouring them, and can be used immediately or stored for as long as a month. But if left for as long as one hour they should be dipped in water before using. And if stored for as long as 24 hours they should be soaked in water for at least an hour before using. Operators sometimes forget this precaution, with the result that investments may crack and castings be spoiled.

Physical Qualities of Investments

Physical Strengths. The ideal investment would retain physical properties stronger than those of any metal until the cast metal had cooled through its mushy range and begun to solidify, after which the investment would become weak. But the weakening might be desired to be selective as to areas and progressive as to retained strengths. If shrink of the metal was to be restrained at some areas of the castings, the investment would remain at full strength at those areas. If there was any danger of the castings bending or distorting from lack of abilities to sustain the weights of their own sections through their plastic temperature ranges, the investment would remain strong enough to prevent this. Otherwise, the investment would weaken and become crushable at such progressive rates as never to oppose the shrinkage of the metal in any way.

Obviously, no such investments have been compounded. No one formula could be universal; the strengths and periods of strength needed for various alloys and contours of castings would differ. But the ideal can be approached, at least remotely.

Kinds of Strength Properties. Strength properties needed in investments are tensile, compression, and cohesion (resistance to spalling). For fragile cores or projections, shear strength may be needed. And for fragile members of some contours, notch sensitivity should be controlled. Shock resistance rarely is low enough to be important, but there have been instances of special investments which were so fragile that they had to be "handled like egg shells" when being taken from the heat-up furnaces to the casting machines.

Tensile strength is needed to resist the expansion forces imposed by the patterns during the melt out, and the hydraulic forces of the molten metal during the pouring. Even more, tensile strength must be sufficient to hold against the inevitable temperature gradients between various sections of the investment during the heating up. These gradients can be controlled at all operations other than the casting one by doing the heating or cooling slowly, although the greater the slowness the higher the operating cost. But when the hot metal goes into the cavities, the temperature gradients are severe, abrupt and local. Metallurgical qualities of castings sometimes are sacrificed because the investments, if cool enough to provide those qualities, will not withstand the thermal shock of the temperature gradient. Those sacrifices rarely are necessary.

Compressive strength is needed for the same reasons as for tensile, and also to prevent spalling. Hardened investments consist of binders and aggregates and have the structural natures of concrete. When any such material is deflected under compression, it tends to fail, not as steel would fail at the surface at which tensile stress is imposed, but by a crushing action at the side which is under compression. For further information regarding characteristic failures of concrete materials under compression, reference should be made to the literature.

A representative tensile-compression stress diagram of an invested flask at the time of pouring the castings would be almost hopeless to try to work out. It must be recalled that the hot metal never simultaneously impinges on all surfaces of any cavity and rarely enters any two cavities at the same instant, that the resulting stress-strain components and their compoundings as imposed by expanding areas upon areas which are expanding at lower rates are almost infinite in their possible variations, that the situation in a two-coat investment can be quite different from that in a one-coat one, and that the behaviors of curved or of interrupted surfaces will be different from those of straight and uninterrupted ones.

Compressive forces cause spalling. The spalling is greatest, all other factors being equal, on large flat areas. The compressive strength of the investment must be sufficient to withstand the forces. The spalling may be at areas of the investment other than the cavity surfaces, in which case it often results in cracks which lead from the spalled area to the area of expansion-tension at the surface of the cavity. Either the spall or the crack will ruin the casting.

Cohesion of the investment must prevent individual ceramic grains from being dislodged under the abrasive action of the entering metal, and also must cause the tensile and compressive forces to be transferred or "divided" among the various areas of the investment.

Weakness Sometimes Wanted. All strengths must be sufficient to hold the positions and shapes of the cavity members until the cast metal has solidified. But when the metal begins to cool, and if shrink restraint has not been planned, weakness of some members may be highly desirable. Cores must break off from the cavity walls so as not to build shrink-strain areas about themselves. Cores must crush. Walls must fracture or spall.

The disintegration of the cavity must not be sufficient to allow the casting to distort from the weight of its heat plastic members, nor from centrifugal forces which may be under application in centrifugal casting.

Balancing of Strengths. The important point, then, is to secure the balancing of strengths needed for individual casting problems. And this is the basis for many decisions about investment materials and methods.

Plaster of Paris, for example, is an ideal material for many of the bronzes and other nonferrous alloys, but it does not have high enough strength for many applications of these alloys. A single coat investment usually is less costly and always is less bothersome to apply than a multiple coat one. There is no alloy for which single coat types do not exist. But there are strength factor combinations impractical to secure with single coats but easy for multiple coats.

Sources of Strengths. Several factors may be combined to control investment strengths.

One investment material can have three times the inherent strength of another. Filler or ceramic ingredients can be varied for strengths, or proportions of vehicle to dry material. In one example, using the same ingredients but varying the amounts of water as a vehicle, at the end of one hour of setting time with 28 cc of water to 100 grams of dry mix the tensile strength was 128 psi and the compressive strength 1,020 psi. But by using 33 cc of water to 100 grams of dry mix the tensile strength went down to 122 psi and the compressive strength to 870 psi. Obviously, if lower compressive strength for easier crushing action was wanted, the proportions of vehicle would be increased.

Strength can be controlled in some investments by varying the setting-up time. In one instance, at the end of one hour of setting time an investment had compressive strength on the order of 1,000 psi, but after seven days that strength was on the order of 2,800 psi. The set-up strength can go too high.

Thicknesses of sections affect strength. In one example a casting house was using a high specific-gravity, extremely strong, high thermal-conductance investment. Control of the metallurgical qualities of castings was excellent but many castings were broken when getting this hard and strong material off from them. A lighter weight, less strong and hard, lower thermal-conductance investment was tried, with thicker wall sections and a heavier flask to increase the strength. The heavier flask acted as a chill to compensate for the low thermal conductivity of the new investment. Results with the second investment were equally good and the broken castings problem was solved.

Relation to Costs. A stronger investment material sometimes can be used in less bulk per flask, resulting in a lower unit volume cost.

Flasks vs Strengths. The flask can contribute a great deal to the strength of the investment. But if a high strength investment is used, a very thin flask may be sufficient, or in some instances the flask may be removed before melting out and heating up. Since scale-resistant flasks are somewhat high in cost and are not indestructible, the reduction of costs may be important.

Flasks for high strength investments always can be weldments. They need not be of the alloys which are extremely strong but are low in thermal response and therefore difficult to weld. This makes it easier to manufacture flasks for high strength materials to special shapes in accordance with clustering problems. And if the flask is not to go on through the heating-up cycles, it can be made in separable members and there are no limitations on the metals or other water-resistant materials of which it can be made, nor upon its dimensions and contours.

Thermal Conductivities. Zirconias, aluminas and magnesias in investment materials are high in thermal conductivities; silicas are low; the range among other materials or obtainable by blending is wide. The fineness of mesh of the refractory makes a difference, a fine mesh in the same refractory generally resulting in an investment of higher thermal conductivity.

When thermal conductivity is high, especially if a flask is used and the investment is strong and therefore can be thin-walled enough to act as a chill, the dissipation of heat from the cast metal will be outward and rapid enough so that progressive deposition of metal will be from the outward areas of the casting cavities and will be under control.

Also, when thermal conductivity is high, it is possible to place the casting cavities close together so that the heat from one casting will be conducted to any neighboring casting which is cooler than itself. The resulting uniform slow cooling sometimes is highly desirable. The direction of escape of the heat, whether outward through the investment walls or backward through the exposed end of the sprue, is controllable by varying the thickness of the investment wall which is outside of the cavities.

If it is desired to heat the castings by quenching the entire invested flask and its contents, or to remove the investment by plunging it into water while hot and thus causing it to disintegrate by thermal shock, high thermal conductivity can be helpful. High conductivity also can help to distribute the thermal strains within the investment and can permit more rapid heating up.

Low thermal conductivity sometimes can better accomplish objectives of controlled slow cooling.

Surface Qualities of Castings. If the dispensable pattern has a completely smooth surface, the smoothness of surface obtained on the casting depends almost altogether upon the investment. Several factors are involved. Among them:

Chemical Effect. Any slagging, oxidizing or other effect of materials which may be in the investment or at the investment surface, will affect the cast surface even if there is no chemical reaction with the metal itself. Reaction with the metal is, of course, highly destructive to surface qualities.

Erosion Effect. If refractory particles are eroded either by the patterns or by the entering molten metal, they are likely to embed themselves in the surfaces of the castings.

Persistence of Permeability. If air cannot readily escape from the investment cavities, and if gases cannot also escape from alloys which exude them, casting surfaces will be bad. But since any slight fusing or slagging of the investment tends to shut off this escape, the original permeability may not persist. This has a bad effect upon casting surfaces.

Particle Size. If all other factors are under control, the sizes of refractory particles at the faces of the investment cavities determine the smoothness of the casting surfaces. Casting houses are resorting to air flotation to obtain finer particles than can be separated by sieves. But these particles have to be held by bonds adequate to prevent erosion while maintaining permeability. Since pore sizes and therefore permeabilities become smaller as particle sizes are reduced, it generally is easier to maintain permeability if the extremely fine particles are a facing over much coarser ones. This condition is most easily obtained by the multiple coat method, the fine particles being applied first and then the heavier secondary investment body.

Permeability of Investments

"Permeability," as applied to investments, means the ability of air to escape from the cavities by permeating into, or passing through, the porous structure of the investment. This escape may be necessary in advance of pouring the castings if vacuum casting is to be done and the vacuum is applied to the investment before the pouring is begun. But in the great majority of instances permeability simply means the ability of the entering molten metal to push the air out of its way.

Permeability can exist in several forms, very few of which ever have been scientifically measured. Most of the knowledge of permeability has been obtained by practical experience within the casting houses.

Behavior of Air. The behavior of the air as it permeates the investment never has been measured but can, to some extent, be visualized. Some of the factors are:

(1) In a hot investment, the kind most commonly used, the air may have traces of high temperature steam, but will approach the behavior of a perfect gas. This gas will be thin and light in weight in accordance with the temperature.

(2) But in a cold investment there may be moisture and the air can take on some of the high energy properties of superheated steam. The air as a gas will be denser; there will be more weight of it for a given volume within the cavities.

(3) The entering molten metal will not be a perfect piston operating in a perfect cylinder but will be rolling and eddying in accordance with the laws of hydrodynamics. It will tend to entrap air if the air is under high enough pressure.

(4) To the extent that the air is compressed by the entering metal, the temperature of the air will rise.

(5) The air will pick up heat from the molten metal and the air pressure will rise accordingly. With this rise, especially if accompanied by superheated steam within the air, the tendency to force itself into any

opening presented by the turbulent metal or even to form a channel through which it can escape along the face of the metal through the runners and sprues will be increased.

It is clear that the permeability properties of the investment need to differ in accordance with the temperature of the invested flask, the temperature of the molten metal, the characteristics of the gates and runners and sprue as flow channels, and the flow characteristics of the metal as a liquid. There are no ways of measuring the combined effects of these properties except by imaginative visualization, experience, and trial and error.

Effects of Pore and Channel Sizes. The air enters the investment through openings or "pores" at the cavity faces. These pores may be of almost any shapes, but in accordance with the laws of geometry the area of each of them diminishes far more rapidly than does the diameter or other transverse measurement. And this area determines the amount of air per second which can enter at a given pressure, the effects of turbulence within the air being ignored for the sake of simplicity.

Each pore leads to a channel between grains of refractory material. The channels seldom are uniform in sizes and shapes along their lengths. But the capacity of the channel in volume alone decreases far more rapidly than does its cross-sectional size. And the effects of friction to limit the passage of air increase rapidly as the channel size is reduced.

Each channel in turn leads to one or more other channels. The connecting orifice may be larger or smaller than the smallest cross section of the channel. The second channel may be larger or smaller than the first. Their junction may be at any angle or of any shape, with all kinds of turbulences induced in the air to reduce the volume and velocity of its passage.

The lengths of channels can vary. And with every increase in length the factors which reduce the passage of air become very much more powerful.

Modifying these effects is the fact that when pores and channels are small there are more of them. But experiences reported by casting houses do not record many instances in which a small-grained and fine-pored investment had as high permeability as a large-grained one, all other factors, such as the tendency of the bonding agent to fill up small channels, being equal.

Differential Permeabilities. By the multiple-coat investing method it is practical to use extremely small-sized refractory particles at the surface of the cavity and back them up with larger sizes. The immediate effect of this is to shorten the fine-sized channel lengths and reduce the frictional and other capacity losses and thus to permit more air to pass through them.

Another effect is to increase the escape of air by postponing the point at which back pressure becomes effective. If there is air in these large secondary passages, it will constitute a back pressure against the tiny passages. But according to Napier's formula this back pressure has no effect whatever until it reaches a critical pressure which (for air) is 52.8 per cent of the flow pressure of the tiny passages. The pressure in the tiny passages is built up by the entrance of molten metal into the investment cavities and by the increase in temperature of the air within those cavities. Up to the point where the back pressure is 52.8 per cent of all this, the tiny passages discharge as if there were no back pressure, as if into a vacuum.

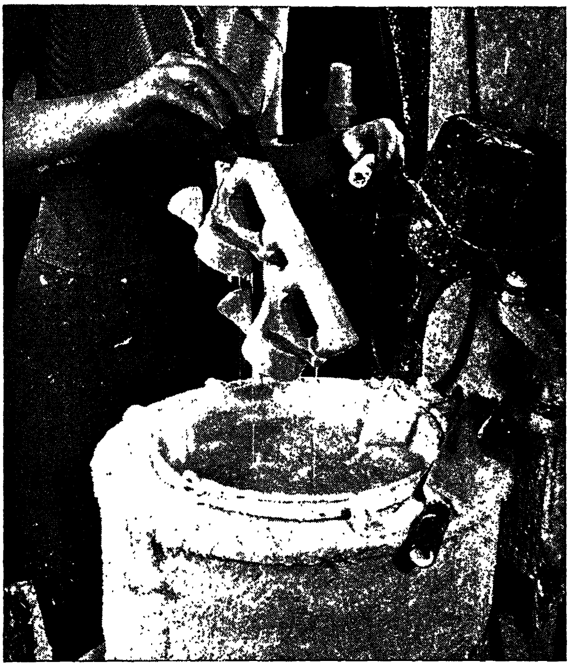


FIGURE 105. Dip-coated investments have differential permeabilities.

If the initial passage at the cavity face discharges into one of about its own size, and that in turn to one of the same size, etc., the back pressure builds up rapidly. But if a tiny passage discharges into one of much larger volumetric capacity, and that one into another of large capacity, the back pressure can build up in these larger passages no more rapidly than the air coming from the tiny passage is able to fill them. And since the air also will be escaping from the larger passages, the critical pressure may never be reached within them.

What actually happens within an investment, of course, is that one tiny passage discharges into a succession of others and at the end of this chain a larger chain is reached. By this time the back pressures within the tiny passages themselves may be high and the pressure at the last one reduced.

All of the factors such as total lengths of chains of tiny passages, net losses by friction and by turbulence, and net effects of back pressures, increase in abilities to restrict the flow of air through tiny passages with the thickness of the section containing the tiny passages. When fine-grained refractory areas are to be backed up by coarse-grained ones in order to secure differential permeabilities, it is important to control the thicknesses of the fine-grained areas.

Directional Permeabilities. When the investment material is subjected to vacuuming after being poured over the cluster, the air bubbles tend to travel in the direction of least resistance through the material. That direction is generally upward, first, because the vacuum is less effective at the surfaces in contact with the flask and with the base, and second, because air tends to rise within the liquid investment.

The direction can be modified somewhat, but only somewhat, by the use of a thick and porous asbestos paper lining within the flask.

The effect is to cause the grains of refractory material to tend to align their longest axes in the direction of air travel. This creates a natural direction of travel for the air which later permeates the investment. The direction is generally parallel to the sprue. The effect is greatest at the topmost part of the cluster, since air can travel more easily between the investment material and the pattern material than through the investment material and therefore most of the air will reach the topmost part of the cluster before quitting the cluster. This effect has been known to be great enough so that the investment was weakened by the air passages at the top of the cluster and the end of the investment broke through under the force of centrifugal casting.

When air is removed and fine grains of refractory material are caused to rise by vibrating the investment after pouring, this same directional effect is obtained although it may not be so pronounced.

Invested flasks have been cooled, filled with mercury, and then molten metal poured into them. The mercury vaporized, the vapor permeated the investment as air would do, and when the flasks were cooled the mercury solidified within the investments. Careful cutting apart of the flasks thus permitted the mercury to show how and where the permeation had taken place.

Since these investments had been vacuumed, the lines of permeation all led to the topmost parts of the clusters. It was clear that air from the first cavities to be filled by the metal could follow these paths of permeation and increase the air pressures in the last cavities to be filled, thus producing bad castings within those cavities.

The directional permeabilities are not so pronounced that the channels act like pipes. Rather, an area of high permeability is formed in the vicinity of the cluster, and although the permeability may be higher at the topmost part of the cluster, the air is generally free to travel in any direction within the high permeability area.

No matter how the metal is cast into the invested flask, whether by centrifugal force, pressure or gravity, there will be some cavities which fill later than others. Any bad effects of directional permeability are likely to be felt at the last cavities to fill. These cavities therefore often are used as risers. Vacuum casting alone can escape this, and since the vacuum is never complete, the escape is never complete.

In multiple coat investing the directional permeability zone is likely to be outside of the coats which are immediately in contact with the cluster. Any bad effects of directional permeability thus are greatly reduced.

Guided Permeability. When it is desired to make sure that the air escapes from an intricate core or other area of a casting, it is possible to use an investment section of unusually high permeability at that area. This section usually is incorporated as a protruding insert when molding the dispensable pattern, the protrusion being made long enough to extend to the outer surface of the investment. This practice is not common, but is capable of solving many problems.

Reversed Permeability. When the cast metal solidifies in the investment cavities and begins to shrink, it either creates a void between itself and the cavity walls, or else clings to the immediate coating of investment material and causes that coating to shrink with it. In the almost endless combinations of pressure phenomena which can be created in the vicinity of the casting, any air which exists in that area of the investment is likely to impinge upon the surface of the casting. If the alloy is subject to rapid oxidation at those temperatures, surface damage will occur to the extent that air is present or more air can permeate from outside the investment.

This damage from reversed permeability is least if the investment area in immediate contact with the alloy has very fine passages, provided that that area is not fractured. But that area may be required to fracture or even crush in order to save the casting from shrink strains. This difficulty often leads to triple coat investment techniques, one coat being extremely fine-grained for fine surface, the second of larger grains and greater thickness to reduce reversed permeation, the third or main body being of coarse grain and higher permeability.

Chemical Permeability. The first, or first and second, coats sometimes are made of very fine-grained refractories and a third but very thin coat of carbonaceous material. If the flask is not heated to a temperature which will volatilize the carbonaceous material, this material will volatilize only when heat from the cast metal penetrates to it. Upon reversed permeation the carbon gases are carried to the surface of the casting and serve to reduce decarburization or otherwise to act as reducing agents.

The entire technique of incorporating reducing and other chemical agents in investments with the intent that they shall act at the metal surface at the time of reversed permeability, is rapidly developing. Its full potentialities were unknown at the time this text was written.

Permeability vs Materials. Some binders of the refractory investment grains tend to vitrify at high casting temperatures. If this occurs before the castings are poured, it tends to reduce permeability. If the occurrence takes place as, or immediately after, the molten metal strikes the cavity surface, the effect may be to decrease reversed permeability but also to "burn in" or to incorporate the vitrified material with the surface of the casting. Many attempts are made to balance these phenomena and thus to obtain high initial permeability with low reversed permeability. In the absence of success in these attempts the rule is: "The lower the proportion of bonding agent the higher the permeability, all other factors being equal."

Permeability vs Expansion. By the multiple-coat method, or by otherwise making different areas of the investment of different materials, it is possible to obtain differing coefficients of thermal expansion.

Unless restricted, each particle of the investment material tends to expand the same per cent in all directions with the result that each particle becomes larger and the channels increase in size with consequent increase of permeability. But if opposed, depending upon the elasticity and plasticity of the material, the expansion tends to go toward the direction of least resistance, with the result that the passages and permeabilities are reduced. Since the plasticity generally increases with temperature a point may be reached at which the expansions of particles greatly reduce the passages.

Up to that point, all other factors being fairly equal, the investment section having the highest coefficient of thermal expansion will open the widest passages and permit directional control of permeability accordingly. If the temperature exceeds the point of plasticity, as they begin to cool and shrink the investment particles may close the pores or passages tightly, thus shutting off the reverse permeability.

Since the temperature usually is highest in the vicinity of the cast metal, the expansive closing of the passages is likely to be greatest in that area. If this is not desired, the material having the highest coefficients of thermal expansion are confined to the outer areas of the investment.

Cyclic Permeability. When binders which tend to vitrify are combined with investment materials which become plastic in a coating which is close to but not in immediate contact with the surfaces of the castings, the intention being to provide high permeability when pouring the casting but cause low reverse permeability immediately afterward, the investment sometimes is said to be one of "cyclic permeability."

Melt-Out Problems

The forces generated within the pattern cluster while the investment material is setting and during the early stages of melt out have greater effects upon the qualities of castings, and especially upon surface qualities, than were appreciated during the early stages of the precision investment casting art.

Exothermic Reaction. When the common types of investment materials set up, they have exothermic reactions (they give off heat) and they expand. Because of the heat the dispensable pattern material also expands. If large enough in dimensions and heavy enough in sections the pattern may damage the partially hardened investment. This is one of the problems of castings which are over 2 inches on any dimension, and one of the reasons for the use by some houses of investment materials which set up very slowly and retain some of their plasticities for most of their set-up periods.

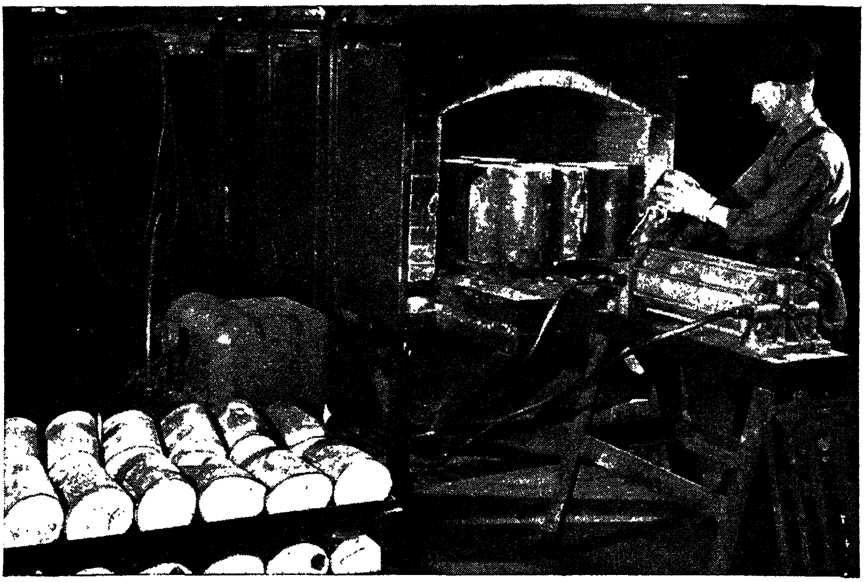


FIGURE 106. Invested flasks entering a melt-out sequence.

If the investment is allowed to stand at room temperature after setting up, it retains most of this expansion but the pattern shrinks, leaving space between itself and the investment wall. During that shrinkage particles of investment material can be broken from the cavity walls and, on occasion, fragile cores or other inserts can be fractured. Therefore many investments must be melted out before the patterns cool and shrink.

Upon reheating for the melt out and the burn out the investment again expands. But the pattern material generally has a higher coefficient of thermal expansion and almost always has higher thermal conductivity. Therefore a race is begun to see if the pattern material can expand to reoccupy the space between itself and the cavity walls and then further expand to damage the walls before becoming heat-plastic enough so that it will do no damage.

If the pattern material has expanded into heavy pressure contact with the walls and then goes through one of its thermal inversion periods in which it shrinks momentarily before continuing to expand, the chances of its doing rubbing damage to the walls are excellent. Against these hazards several defenses can be interposed.

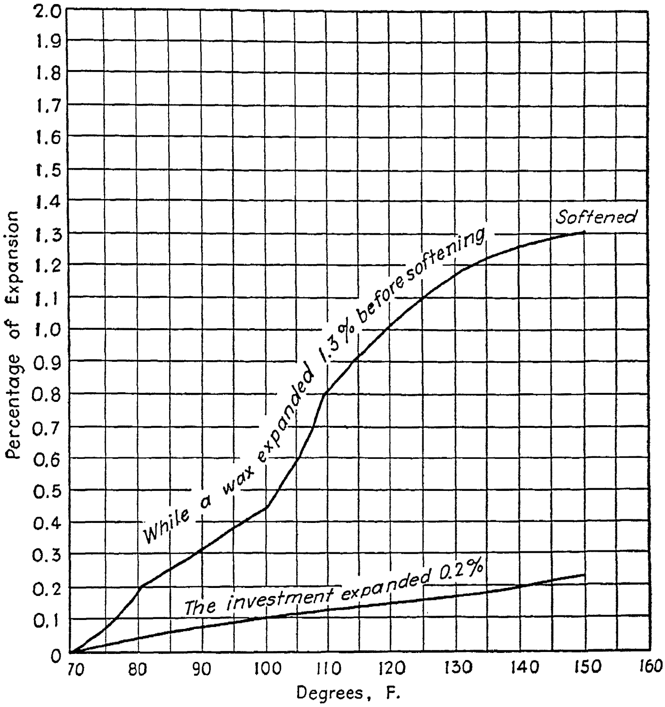


FIGURE 107. The pattern material expands much more rapidly than the investment.

Varying the Temperature of the Vehicle. Especially when the vehicle is water, if the vehicle is hot the pattern expands and the investment sets up quickly. If the vehicle is cold, the pattern shrinks and the investment sets up slowly. Uniform vehicle temperatures of 70 to 80 degrees F generally are recommended. But some of the largest casting houses keep their mixing water at 100 degrees F plus or minus 2 degrees. And problems of large dimensions and sections have been solved by using the mixing water as high as 120 degrees F.

The exothermic nature of the setting reaction is not cancelled by the higher temperature of the water. And with this temperature the pattern expands closer to the dimensions it will have at its softening temperature and thus will impose lower stresses on the investment while melting out.

Varying the Amount of Vehicle. When lower proportions of vehicle are used, especially if the vehicle is water, the setting expansion and the heating-up expansion of the investment generally are increased, with consequent reduction of pattern expansion problems.

Oven Setting. With a single-coat investment of slow-setting characteristics, the investment may be poured and vacuumed at room temperature and the entire flask placed in an oven and held at 120 degrees F during the complete setting period. The wet investment then will expand somewhat before it begins to set at all, and the patterns also will be undergoing thermal expansion. This mutual movement of the surfaces tends to rub the soft investment against the cluster and cause the investment to follow the pattern surface contours very closely. The 120-degree temperature is only 5 to 10 degrees below the initial softening range of the pattern material; therefore the patterns will expand very little more before they begin to flow.

Usually, the invested flask is transferred directly to a true melt-out oven when the setting is completed. But if the flask is cooled to room temperature, the contraction of the pattern material will leave plenty of space for re-expansion upon melt out, and cavity wall damage will be minimum.

Cyclic Expansion. An investment of high thermal expansion may be used. But if this is done, the need to heat up slowly in order to avoid temperature differentials between sections may be costly, the total expansion at casting temperature may be great enough to make calculation of pattern sizes for dimensional accuracy difficult, and there may be a final thermal expansion when the hot metal is poured in, this last being damaging to the casting, if great enough. The problem may be solved by the use of ingredients which cause the thermal expansion curve to level off at a predetermined figure. Finely ground glass, water glass, magnesias and other ingredients are used for this purpose. Many of the proprietary brand investments have these levelling-off points. Cyclic expansion of this kind can solve the problem of quick expansion during the melt out followed by controlled expansion at the casting temperature.

Use of Steam. If some free water or other vehicle remains within the investment body at the time of melt out, several purposes may be served. The liquid acts as a lubricant, or combines with the lubricity of the pattern material, to ease any rubbing action of the expanding pattern on the investment wall. The liquid acts as a conductor of heat through the investment, aiding in initial uniformity of expansion and avoidance of temperature gradients and bringing the investment expansion more nearly into line with that of the pattern. Steam or other gaseous pressure is generated between the cavity wall and the pattern material, aiding in the expulsion of the heat-softened pattern material.

This steam action is one of the principal reasons for soaking a plaster of Paris investment which has stood too long. But the technique is practical only for an investment which is permeable to the steam or other gas as well as to air.

Water Plus Vacuum. If the investment is permeable to water, vacuum may be applied and maintained at the sprue end of the invested flask and the invested flask immersed in boiling water. The water will penetrate to the pattern material, loosen it, and heat it above the molten temperature for most pattern materials. The vacuum will draw it out. This technique has been known to reduce damage to the casting cavity surfaces to the point where it produced the most beautiful casting surfaces ever obtained.

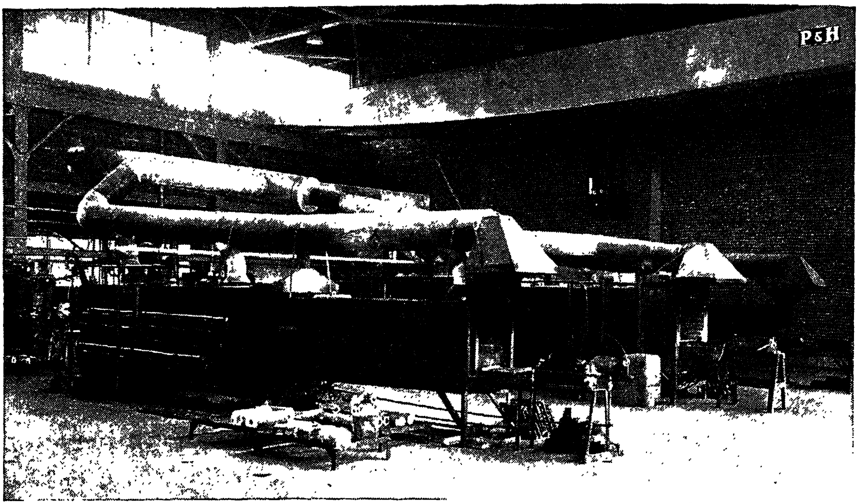
Other Techniques. Vacuum methods can be combined with any heat sources. Infrared ray ovens have been used for heating invested flasks while vacuum was applied at the sprue ends, and so have induction heaters.

For Low Temperature Casting. These vacuum melt-out methods are especially good if the invested flasks are to be at less than 800 degrees F when the molten metal is poured. They avoid the need for heating the flasks to the complete vaporization temperatures of the pattern materials and then risking the thermal effects of cooling them down to the casting temperatures. Flasks for such high thermal conductivity alloys as aluminum may be packed in Dry Ice for several hours before pouring, and it is important that they never be broken by cooling down from high melt-out temperatures.

Melt-Out Equipments. If melting out is to be a separate operation from heating up the flasks, as it nearly always is, the equipment for it consists of ovens rather than of furnaces.

If high-speed melting out is to be used, with the invested flask at room temperature placed directly into a chamber having a temperature of 800 degrees F, the equipment is an open muffle furnace.

The controllability of this apparatus determines whether the melt out is to be a controlled operation or is to run wild. With some investments, particularly with plaster of Paris, it can be permitted to run wild provided no dimension of any casting is over 1 inch and no thickness of section is greater than 0.125 inch. But in most instances, precision control of processes is the most valuable ingredient of the investment. For this control the equipment needs several features:



(Courtesy Haynes Stellite Co., Kokomo, Ind.)

FIGURE 108. Melt-out furnaces with ample hood exhausts, in high ceilinged, well-ventilated room.

(1) Contact between the investment material or its gases and any flame or other ignition source must be impossible during all but the last stage, the "burn out" stage, and most of the modern shops avoid the burn out. Once the investment material catches fire, temperature control of the investment becomes impossible and the explosion hazards become great.

(2) The atmosphere within the oven and about it must be carefully controlled. Some shops prefer a mildly oxidizing atmosphere but not one containing sufficient oxygen (air) to cause fire. But most shops recirculate the non-oxidizing products of combustion of gas or oil burners within and about the ovens. This latter also is an economy measure since it makes use of waste heat from other processes.

(3) Exhaustion of gases and of volatiles should be complete, preferably by drafts induced by blowers in the exhaust stacks. The exhaustion should be under complete temperature as well as volumetric control until the products reach either the open air or the scrubbers which are to remove

them from the air. If products condense in stacks or passages they can become explosion hazards.

(4) Safety precautions should take cognizance of the facts that the products of combustion of many plastics materials are highly poisonous, that waxes at high temperatures can give off acrylic acid which is poisonous and which has been known to render men unconscious when exhausted into a closed room, and that the fumes of alcohol which often is used as a vehicle can make men psychologically unfit for their work if breathed in small quantities and can be highly poisonous if breathed in large quantities.

(5) Peep holes or other safe ports should be provided for observing the progress of the process. Opening the oven door for this purpose has been known to cause an explosive blast of flame when the air struck the gases and volatiles from the investment materials, and also has been the cause of igniting the materials and ruining the investments.

(6) The oven temperature should be controllable by small increments. The temperature should be capable of sensitive control when:

(a) The pattern material reaches one of its known critical ranges or inversion temperatures. Holding the temperature at this point, or even slightly reducing it, can reduce the violence of the action upon the walls of the investment cavity.

(b) The volatilization point of the vehicle is reached. This is 212 degrees F for water, lower for alcohol and most other vehicles. Holding the temperature at this point can reduce the violence of the escape of the gases confined within the investment, since violence of partially confined gases is caused by pressure and pressure by temperature. Up to the volatilization range it often is best to raise the oven temperature more rapidly than the investment can follow, thus heating the exterior areas of the investment first and causing their vehicle gases to get out of the way of those in the interior. The oven temperature then is reduced to hold the entire investment at vehicle evacuation temperature.

(c) The pattern material begins to move out, especially if it is to be salvaged. If vacuum is being applied to the sprue, this temperature may be fairly low. If gravity flow alone is used, the temperature may be held for hours at the lowest flow point, the "ooze point." If steam or gas pressure of the vehicle is used, the temperature may be raised slowly to the flow point and then raised rapidly to the vaporization range of the vehicle.

(d) If the investment material has an inversion range, the temperature should be held constant or even reduced slightly when this range is reached in order to reduce the violence of the reaction. And since there may be several coats or areas made of different materials and having different inversion points, there may be an equal number of these temperature control points.

(7) The exhaust blowers should be capable of variations in speeds and of close control. To maintain a constant flow of gases through the oven they need this control for the same reasons that high altitude airplanes need variable pitch propellers. The exhaustion should be slow while the pattern materials are flowing out of the investments, more rapid at the temperatures which produce noxious gases, most rapid immediately before and during the opening of the oven doors to remove the flasks. This last action is a two-way safety precaution. It serves to protect personnel and equipment against flash backs from any explosive gases which may be striated or otherwise lingering in the ovens. And it uses the high temperatures existing in the oven at this time to clean out of the exhaust stacks any volatile materials which may have condensed in them, and thus reduces the hazards of stack explosions at subsequent melt-out operations.

Melting out is, then, a "cyclic" operation which needs highly controllable equipment. It is best done under automatic control of temperature, of exhaust stack draft, and of atmosphere within the oven. Under the best conditions these factors are controlled by instruments of the kinds commonly used at power plant furnaces and in heat-treating rooms. The instruments keep chart records.

One oven, or a series of ovens or chambers may be used. In most of the large houses the series method is used, the flasks travelling automatically from chamber to chamber, the hot gases from the higher temperature chambers being used to heat and to control the atmospheres of the cooler ones, but these hot gases being the products of combustion of the heat sources only and including none of the heat products of the investment materials. Each oven must be capable of temperature ranges more than adequate for its complete cycle. The highest temperature commonly used for any part of the melt out is 800 degrees F, all higher temperatures usually being part of the "heat up" in preparation for casting.

Burn Out Sometimes Practiced. It has been emphasized that the pattern material should not be allowed to catch fire, that it should volatilize out rather than burn out. But there is one technique sometimes practiced when production lots are large, no recovery of pattern material is desired, and the shop has plenty of capacity in its exhaust stacks and blowers.

The invested flasks are soaked in water so that steam will be generated within the cavities and the pattern material will be forced away from the cavity walls. Then the flasks are placed directly into an oven at 800 degrees F. They are pushed continuously through this oven and into higher temperature ones.

The pattern material runs out rapidly and catches fire. A forced draft of air is blown through the oven, air being fed in sufficient volume to keep the furnace temperature down and to carry most of the heat of combustion up the stacks and away from the flasks.

This practice results in high speed production but is not recommended for any but the very largest shops.

Problems of Pouring and Mixing

The properties desired in the invested flask and the general methods of designing, handling and melting out the investment to obtain them having been determined, the casting house must consider pouring and mixing techniques.

Flask Linings. The size, shape and strength of the flask are determined by the geometrical needs of the cluster and by the physical strength of the investment. See page 250.

The flask may be lined with asbestos paper, with water-repellent wrapping paper, or with ordinary paper. Or it may not be lined at all.

There are several purposes of the lining, among which are the following:

(1) It is a resilient member against which the investment may expand sideways while setting. Without this the expansion is confined to a vertical direction and, especially in large investments for large clusters, may tend to distort the investment cavities or to set up strain weaknesses within the investment.

(2) It forms a surface which has less frictional resistance to the movement of the investment along the flask wall while the investment is expanding vertically.

(3) It provides an air-permeable space along the flask wall. Within this space the air can move during vacuuming, thus modifying the tendency for all of the air bubbles to move vertically through the investment under vacuum. And when pouring the castings this air-permeable surface again is of value.

(4) It provides a resiliency which is of assistance when vibrating.

(5) Its permeability provides paths of escape for volatiles when melting out, and paths of entrance of water to the investment when soaking in water or when using the boiling water and vacuum technique for removing the investment.

(6) It can reduce heat damage to the flask if the flask travels with the investment through the melt out and the heat-up processes.

(7) It can be extended above the flask to form a container into which excess products of the investment will rise when vacuuming or when vibrating. A removable rubber collar also may be fitted to the top of the flask for this purpose. In some investments these excess products sink back into the flask so that the flask has to be refilled to its top; in others they remain above the top of the flask and must be sawed off level with the flask top after the investment has set; in others the center sinks and forms a crater but the edges do not and therefore the excess top must be sawed off level with the flask. The sawing can be done after removing a rubber collar. But it also is easily done by sawing through the paper and on through the material.

(8) The paper prevents the investment material from adhering to the flask wall and makes it easier to remove the flask from the investment, either before melting out or after pouring the castings.

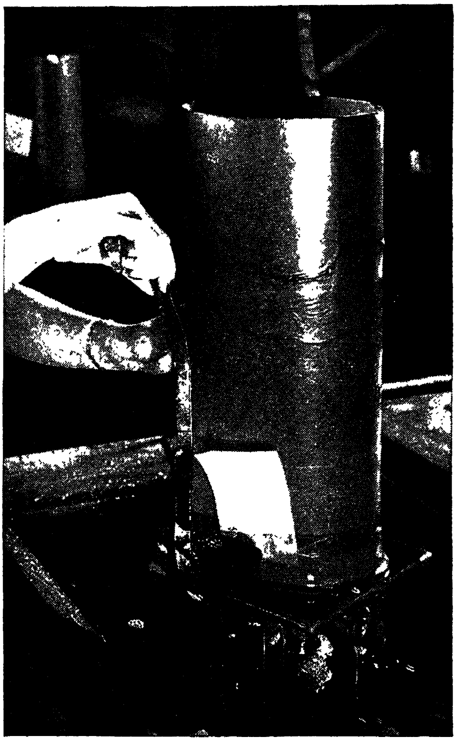


FIGURE 109. Paper may be sealed to the outside of the flask.

Most flasks are lined with porous asbestos paper, lapped over at the joint, and about 0.060 inch in thickness. By using a thicker paper or several plies of this one, the thickness can be increased. Thickness for heavy vacuuming, heavy vibrating, and high permeability should be at least 0.250 inch.

Sawing vs Permeability. The outer surface of the investment while setting up is subject at least to the pressure of the atmosphere, and in addition, to its expansive pressure against the flask and to the pressure of its own weight against the base area. The effects of these pressures may be to form skins of varying thicknesses and permeabilities. Sawing off the top of the investment after setting up removes the skin at this area and increases the permeability.

If the flask is to be removed before melting out, sawing or "scratch brush dressing" off the skin at other areas may still further increase permeability. This is most easily accomplished if the flask is rectangular or otherwise flat-sided, but can be done no matter what the contours of the investment.

Height of Chamber above Flask. The height to which the paper or the rubber collar extends above the flask depends upon the purpose, and commonly is somewhat greater for vibrating than for vacuuming alone. Ordinarily the extension is a minimum of 2 inches for flasks up to 4 inches in height, and for taller flasks is an additional 0.250 inch for each additional 1 inch of height.

To Vacuum or Not to Vacuum. The investment material may be subjected to vacuum immediately before pouring it into the flask and also immediately afterward. The purpose of the first vacuuming is to eliminate air from the investment material itself. The purpose of the second is to eliminate air which may have been entrapped between the dispensable patterns and the investment material.

Other purposes which are served are to impart directional permeability, and to some extent to cause extremely fine grains of refractory material to move to the areas where they will do the least harm in reducing permeability in the vicinity of the casting cavities.

Vacuuming also can have harmful effects. Decision as to whether, when, and how much to vacuum must be based upon several factors. Among them are:

(1) *Speed with which the investment sets up.* Some investment materials take their initial sets within five minutes of their wet mixing. These should not be vacuumed if the air can be eliminated at the pattern surfaces by vibrating or any other means.

(2) *Water vehicle single-coat investments.* If not too rapid in setting up these should be vacuumed after mixing and again after pouring into the flask. By the best methods the pouring is under vacuum. When vacuuming after mixing, the investment will rise in the container, and then will settle back. Vacuuming should be discontinued immediately

after the settling back, lest water be evacuated and the water-powder ratio of the investment be altered. When vacuuming after pouring, the investment may again rise in the flask, then will settle back and begin to form craters from which it "spits."

This "spitting" is an exudation of moisture accompanied by the rise of fine ceramic particles to the surface. Vacuuming generally should be discontinued when this occurs, unless it is desired to evacuate some of the water and raise some of the fines to the top surface. In these latter instances, vacuuming has to be by time cycles which can be determined only by trial and error.

Vacuuming for water vehicle single-coat investments is generally recommended to be at 29.9 inches of mercury, and in some cases is even higher. But a vacuum pump capable of 29.75 inches may cost less than half as much as a 29.9-inch one and the vacuum may be just as effective.

(3) *For directional permeability.* The investment is poured after little or no preliminary vacuuming. All of the vacuuming, or most of it, then occurs within the flask. The paper or rubber collar must be of adequate height to accommodate the swelling of the investment material, usually a minimum height of 2 inches for a 4-inch high flask plus 0.250 inch for each additional inch of flask height. The investment material may sink back below the level of the flask top. So long as no area of the pattern cluster is exposed this will do no harm and the flask may be replenished with unvacuumed investment material after the vacuuming is completed. Vacuuming should not be continued after the investment has settled back.

(4) *Single-coat investments with alcohol or other solvent binders.* There is danger of explosion if vacuuming is too high. No more than 12 to 15 inches of mercury should be applied. Otherwise, proceed as with water vehicle investments.

(5) *Multiple-coat investments.* The problem of eliminating air between the patterns and the investment is solved by prevention at the time the first coat is applied. But vacuuming may be useful to increase the permeability of the main coating and to increase its adherence contact with the first coat and to establish directional permeability. The vacuuming can rupture the first coat. Therefore 14 to 16 inches of mercury should be the top limit. And since the coats sometimes are made with different vehicles having differing boiling points within vacuum, great care may be needed. Ten inches of mercury is considered the top limit when the first investment coat, the one next to the patterns, has alcohol as its vehicle.

(6) *Pattern considerations.* When patterns are molded at low pressures or under turbulent injection conditions, they may entrap air within their interiors. These air bubbles may do no damage whatever unless the investments are heavily vacuumed after pouring. Under vacuum the bubbles may swell up and thus distort the patterns, or may come out

and thus leave cavities which the investment material will fill. Either eventuality means a spoiled casting. Consequently, the casting house may be forced to make a choice between using only low vacuum, no vacuum, or changing to a less effective pattern-molding method.

This trouble may be severe when hollow patterns have been substituted for thick solid section ones to prevent plane protuberance or "bellying." Also, air often is entrapped at the member junctures when using rapid methods for joining cluster units. Breaks filled with investment material which plug the runners and prevent filling of the casting cavities, may be found at these points if the investments are vacuumed.

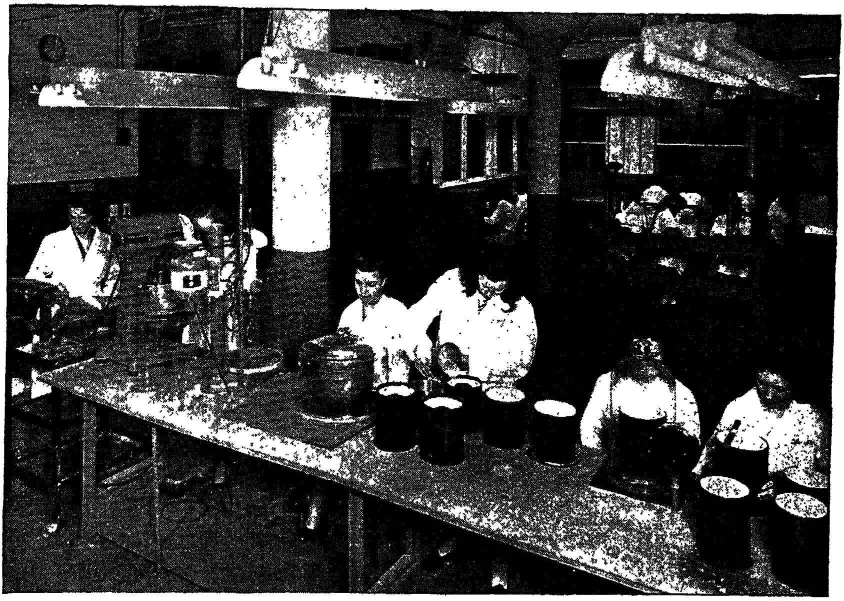


FIGURE 110. Mixing, pouring and vacuuming single-coat investments.

To Vibrate or Not to Vibrate. Vibrating may be used alone, combined with vacuuming, or not done at all. Its purposes are similar to those of vacuuming; to eliminate air, to redistribute refractory particles, to cause better bonding between multiple coats, to eliminate fines, to eliminate excess vehicle, and to control the amounts and directions of permeability. It is somewhat more effective and controllable than vacuuming for every purpose except the elimination of air.

Vibration as applied to an investment has several control factors. Principal among them are direction, amplitude, frequency, and time.

Direction. If the principal direction of vibrating motion is vertical (up and down), the action is a compacting one and the vibration is called "tamping." When the principal direction is horizontal, various particles tend to rise to the top or settle to the bottom in accordance with their densities. The vibration can be reciprocal, circular, or in combined directions (one shake sideways, the next one up and down, etc.).

Amplitude. This means, generally, the distance which the material travels in one cycle of the vibrator. If the motion is reciprocal and the vibrator moves 0.250 inch and returns, this would be a measure of amplitude. Amplitude has no necessary relationship to the force applied to the material, force being more a matter of frequency. High amplitude has a separating action and also an impacting action similar to shot-blasting. High amplitude can cause a secondary coating of the investment to fracture a primary one and also can cause the introduction of air into the investment. The general rule is "work to low amplitude and high frequency." Amplitude also can shake the patterns off from the cluster. Amplitudes as high as 0.060 inch are used in some casting houses but a top limit of 0.001 inch is better.

Frequency. Frequency is measured in cycles per second. When it passes a certain point which varies with the material being vibrated, frequency has the compacting effect of pressure. Pressures as high as 250 psi can be attained when the cycles per second get up among the millions, but these figures are not common to precision investment casting. Frequencies for investments vary from 60 to 3,200 cycles per second, with 60 by far the more common figure.

Split Frequency. A cycle can be made to go at one speed in one direction and another in the reverse direction. If, for example, the motion is reciprocating and the speed is slow in the forward direction and high in the reverse, friction will move particles in the forward direction and inertia will keep them from coming all the way back in the reverse direction. The effects depend upon the relative densities and coefficients of friction of the particles.

Time. This is the time period over which the vibrating is continued.

Overall Picture. The above is an extremely simplified description of vibration. For further information, reference should be made to the literature, especially the literature on the use of vibration as applied to concrete. The average precision investment casting house which wishes to use vibration, mounts a table top on rubber or on coiled spring cushions, applies a harmonic vibrator to the table, sets the flasks on the table, and vibrates them for a minimum of five minutes and for any longer time which is convenient before taking them off. The amplitude usually is beneficially slight. The frequency sometimes is adjustable but usually is that of the "house current" and therefore is 60 cycles per second. The direction is a combined product of the direction in which the vibrator is applied and the responses of the resilient cushions but generally is intended to be tamping. A resilient coupling usually is placed between the vibrator and the table, and since the response of this is likely to be quicker and stiffer in its compression than in its tension stroke, something of a split frequency vibration is set up. Even though the vibrator may have an outright reciprocal motion, the table cushions, because of forces peculiar to themselves, tend to impart a somewhat circular motion to the table top.

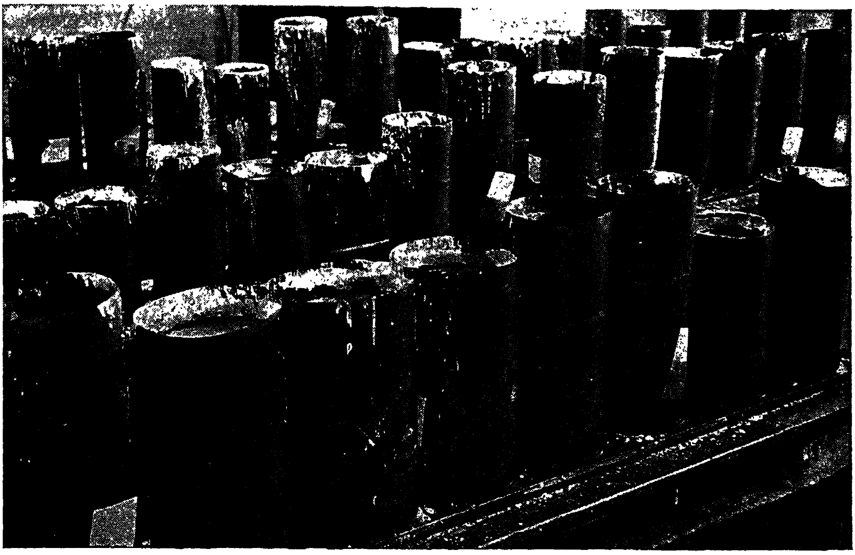


FIGURE 111. Flasks on a vibrating table.

The entire method is worked out by trial and error. And when the apparatus works satisfactorily, the house rarely knows or cares what direction or amplitude it is getting. But a brief study of the principles sufficient to give a mental picture nevertheless can help to improve results.

Filling the Vibrated Flask. The flask is placed on the table and the cluster within the flask. The vibration then is begun, at low amplitude if amplitude is controllable. The investment material is poured down one side of the flask, and if not highly liquid, it forms a sloping bank against the side of the flask. The vibration tends to level this bank off. If there is any split frequency characteristic to the vibration this should be noted and the material poured down the side of the flask which will cause the most rapid leveling off of the material. The material is poured-in no more rapidly than will enable it to maintain a slight embankment. In this manner the air, the excess vehicle and the fines are raised progressively to the top, rather than the excess materials at the bottom having to move completely through the investment body in order to reach the top.

When the flask is filled to the top of the paper or the rubber collar, vibration is continued for five minutes, or for a longer period if inconvenient to remove the flasks immediately. This time period is not known to be critical.

When one flask is filled it is allowed to stand and vibrate while another is being filled, and so on until a dozen or more have been filled; on some tables the number is as high as 50. Then in the same order as they were filled, the flasks are removed. By this procedure the operators work continuously. The production flow by vibrating thus can be smoother than that of vacuuming in which the operator commonly has to wait a minute or so for the vacuum to work and has to take time to remove and replace the bell jar.

Alternative Method. The table top on which vacuuming is done may also be vibrated. The investment is poured into the flask, the vacuuming is begun, the vibrator is turned on, the material rises and falls in the flask, the vibrator is turned off, the vacuum is released. The advantage is that any air bubbles entrapped beneath the patterns are likely to be moved out to where the vacuum can eliminate them. A second advantage is greatly increased elimination of fines with consequent improvement in permeability. Excess vehicle also may be eliminated to a greater extent than is practical with vacuum alone.

If the vehicle is alcohol or some other low boiling-point material, the necessarily low vacuum alone may not be able to eliminate all the air bubbles and the vibration may be needed as a booster. Air troubles in patterns are reduced.

Second Alternative Method. When there is danger of shaking the patterns off from the cluster the investment material may be poured to a point above the cluster before the vibration is begun.

But this does not always help. The fluid friction of the vibrated investment material may do more to break off the patterns than would the vibration alone. A better treatment is to decrease the amplitude and increase the frequency of the vibration, and perhaps also to change the direction by changing the position or "the aim" of the vibrator.

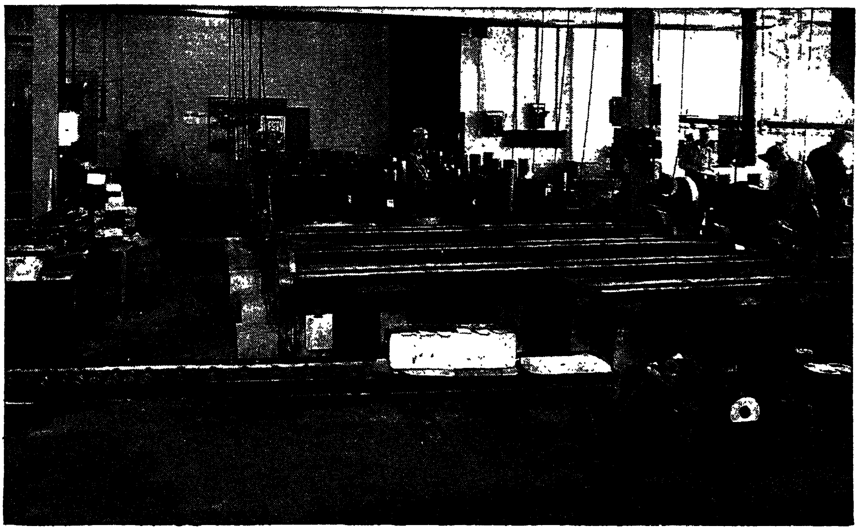


FIGURE 112. Vibration tables.

Cam Type Tamper. A device sometimes used consists of a table top mounted on studs which fit into recesses in the under side in such manner that the top must lift at least 1.50 inches to be removed from them, the top being otherwise free for vertical motion. A cam, an arm or other offset device is fitted to a shaft, the shaft in turn being connected to a motor or other power source. The offset device is brought into contact with the under side of the table top in such manner that the top must be lifted about 0.40 inch if the offset is to pass it. Each revolution of the shaft lifts the table top about 0.40 inch and lets it fall the same distance, thus exercising a tamping action on any flasks placed on the table. The motion could not be truly tamping unless the table were so devised that the motion of the top would be absolutely vertical, and this is not likely to be achieved. Nevertheless the motion is mainly a tamping one, of greater amplitude than is generally to be recommended. The shaft normally makes 1200 rpm, but because of the inertia of the table top and the consequent hammering effect, sometimes is geared or belted down to 360 rpm.

Mixing Methods. Mixing of ingredients almost always is done with the ingredients dry, followed by adding the water or other vehicle, the wet mix. The exception to this is when the dry ingredients are received completely mixed as a proprietary brand and only the wet mixing is done.

Silicosis Hazard. The dry ingredients consist of sand and of pulverized refractories. Rarely is any particle size coarser then 200 mesh, and intermingled with these larger ones will be particles as fine as 1100 mesh. The silicosis hazard if these particles float in the air is extreme. The danger does not end when the wet mixing begins, since particles may fall on the floor, become dried out, and get into the air. All mixing stations should be vented in such a manner that air currents pass from the operator and over and around the equipment and out of the building. This usually requires that the mixing equipment be in an especially enclosed room, and be placed close to a wall, and be vented through induced draft hoods, with gentle fan or other draft blowing along the floor and toward the machines. All nearby rooms should be positive in pressure as compared to that room. Some of the better houses have their mixing equipment in totally enclosed, hood-ventilated, glass-walled chambers.

Alcohol Hazard. If alcohol or other solvents are used as vehicles, their fumes must be kept from the work rooms. Alcohol fumes when breathed are more intoxicating than is liquid alcohol when swallowed. Carbon tetrachloride is highly toxic. Almost all such solvents are dangerous to health.

Practical Test for Safety. Any standard test for toxicity of atmosphere and for silicosis hazard may be made. For further information reference should be made to the extensive literature on the subject, especially that issued by the National Safety Council. The representatives of any good industrial liability insurance company may be consulted.

A practical test is to place a small quantity of perfumery or of any strong aromatic in the dry mix, and also in the wet mix if toxic vehicles are used, then to leave the room for a minute or so, carefully removing the perfumery container. A second person, one who has not had opportunity to get the odor on his hands or clothing, then enters the mixing room. If the odor is detectable in the open air of the room, the equipment is unsafe.

This practical test can prove that the conditions are unsafe but cannot prove that they are safe. The standard safety tests as used by skilled inspectors or safety men are preferred.

Dry Mixing. Dry ingredients often are mixed in foundry-type double cone sand blenders. Other houses mix them in ball mills, in tumbling barrels and in small concrete mixers. Paddles, helicoid conveyor sections, other devices common to dry material mixing practices may be caused to move through or with the materials or to be stationary while the materials move against them. A revolving device of some kind almost always is used. The important point is that the action shall not be violent or throw dust. The rpm should not be over 10 or 15.

Dry mixing sometimes, but rarely, is followed by dry tamping, a cam-actuated table top being used, as described for vibrating the flasks.

Picking up the Dry Ingredients. Dry mixing methods blend the ingredients but rarely cause the different grain sizes to blend completely. As a rule the grain sizes will stratify somewhat, those of lower densities appearing at the top of the mixture. Decision then has to be made as to whether to blend them while picking up, or to take advantage of the stratification.

For investments which are to be vibrated, blending generally is considered better. The fines are wanted with the coarse particles even though vibration later is to eliminate them. It is believed that in rising through the mixture they will rub the coarser particles against each other and cause better bonding, and in addition, will create directional permeability.

For investments which are to have extra fine precoats in contact with the dispensable patterns, advantage is taken of the stratification to lift out large quantities of the fines in advance of sifting or of air separation.

If blending is wanted, the scoop with which the materials are lifted must take from every stratum. Where tumbling barrels of vertical open end types are used, or concrete mixers, or troughs with helicoid mixers, or any mixers from which it is practical to scoop while the contents are in motion, the rule is to position the scoop so that it picks up from all strata (from the complete depth of the material) simultaneously. Even so, there will be some restratification within the scoop. But this usually is corrected in the wet mixing.

Where it is impractical to use the scoop while the equipment is in motion, the scoop should take from the complete depths and as quickly as possible after the equipment stops. Restratification may be most rapid when the equipment is at rest. It often can be observed with the naked eye. Its speed depends upon the relative densities of the materials and upon their relative coefficients of friction, wide density ranges tending to speed it up and high coefficients of friction to slow it down. Moisture usually cannot be added to increase adhesion, and therefore friction, since the moisture may cause the material to begin to set before setting is wanted.

If separation is desired, the mixing equipment may be allowed to stand before picking up the desired strata, and gentle horizontal vibration may be applied.

Wet Mixing. The wet mixing equipment should be made completely of stainless steel or of some other material which is resistant to corrosion and abrasion. It should be easily cleanable. Metal particles eroded from the equipment, corrosion products, and bits of previously mixed investment, are highly harmful to most investments and are not known to be beneficial to any. The equipment should be cleaned instantly after each mixing of a quick-setting material, and before any material left in it gets a chance to set.

The equipment usually consists of a bowl with revolving paddles. The paddles should either rub against the sides and bottom with very light pressure or else clear by not more than 0.002 inch. There should be no unmixed areas, no "unscraped corners."

Small open end concrete mixers sometimes are used for very slow-setting investments.

Instructions for mixing as received from the investment makers usually will read in terms of cc of vehicle to grams of dry mix, most such makers having begun their business lives as laboratories. For those more accustomed to industry this can be translated into pounds of vehicle to pounds of dry mix, or ounces to ounces. For example, the most common mixture is 28 cc of water to 100 grams of dry mix. Exactly the same proportions will be obtained if 28 pounds of water are mixed with 100 pounds of dry mix, or 28 ounces with 100 ounces.

The dry mix should be placed in the mixer first, the mixer started into motion, and the vehicle added slowly so as to avoid lumping. But if the investment is a very quickly setting one, adding the vehicle so slowly that the investment will partly set up before it can be gotten out of the mixer should be avoided.

Specially developed and designed mixers can be obtained from the mill supply houses which specialize on the precision investment casting field. Mixers have been rigged by using old drill presses. Where this is done the paddles should have no speeds higher than 100 rpm of the shaft which turns them while the pan is stationary, or of the pan if it turns and the paddles are stationary. The mixing action should in no way be turbulent or otherwise likely to mix excess air with the investment.

There are differences of procedure with various characteristics of investments. When an investment is definitely known not to take an initial set within 10 hours, an amount sufficient for an eight-hour shift may be placed in the mixer at the beginning of the shift, and provided that the mixture can be kept at proper temperature which in these cases usually is room temperature of 70 to 80 degrees F, the mixer can be kept running throughout the shift and investment be removed from it as needed, the mixer then being cleaned out at the end of the shift. But the mixer should be kept in operation so that the investment materials cannot stratify. This often is a preferred practice for houses large enough to have continuous production flow.

Where production flow is continuous enough, it also is practical to feed ingredients to a helicoid conveyor type of mixer and have mixed investment flow continuously from the discharge end, but only a few houses have production flows sufficiently continuous to warrant this practice.

If alcohol or any volatile vehicle is used, large batch mixing is more difficult but sometimes is practiced. Usually, a certain amount of water is used in addition to the alcohol. The water mix then can be continuous, and the alcohol added to batches or otherwise immediately before use.

The ordinary casting house does its wet mixing in batches only, the wet mixing being done immediately before pouring the investment and the mixing equipment being cleaned immediately afterward.

If multiple-coat investing is to be done, the mixing equipment should normally, but not necessarily, be entirely different. The finer the particles, the closer should be the fitting of the parts of the mixer in order to avoid areas in which the mixing is incomplete, as anybody who has mixed a cake in a bowl can realize. For the precoat materials, excess air in the mix should be especially avoided. The same mixer can be used for both finer precoat and coarser second coat only if the mixer is adequate for the precoat. But as a general rule the mixer for the second coat can be much simpler and more rapid in action than for the precoat, and using the precoat mixer for the second coat wears the machine out of adequate accuracy just that much faster.

Single Coat vs Multiple Coat

When all of the foregoing considerations have been weighed, it will be clear that there are highly varied conditions which investments may be required to meet and equally varied types and properties of investments to meet them. The investment material is to precision investment casting what the cutting oil is to machining: the most easily varied tool of the process, therefore the tool which most easily can be made to conform to the needs of all others. Indeed, proprietary makers of investment materials take the same position as proprietary makers of cutting oils and state that they will compound, or tell how to compound, a material adequate for any feasible set of conditions. Lack of knowledge of the process, lack of adequate equipment, and lack of good housekeeping and of adequate production control, of course, are not to be listed among the "feasible conditions."

Dependent upon the alloy to be cast and the intricacy, precision and surface desired, the casting house may have wide or narrow options regarding the investment it will use. And since the options affect costs as well as the general tempo of the production line and the variety of work which can be done without continually revamping the procedures, they should be studied with care. An option which may or may not exist is whether to use a single-coat or a multiple-coat technique.

Single Coat. The single coat, when it can be used, almost always is the least bothersome and costly. The ambition of every casting house is to work out a single-coat technique for every problem. The reasons why this has not been done are similar to those for not developing a lathe which can produce as high accuracy and smooth finish with a single deep cut as it can with a roughing cut followed by a light finishing one. Almost any procedure of production must be broken down into elements if it is to be at its highest precision.

The single coat can make use of nearly all investment materials, and offers the widest options as to setting-up times, expansions, melt-out procedures, vibrating and vacuuming. It does not offer all of the quality control options of the multiple-coat techniques.

Multiple Coat. There is no "one best" multiple-coat technique, any more than there is any one best set of tools which will solve all of the setting-up problems of a turret lathe.

Multiple Coat with Same Materials in All Coats. A single mixture of investment material is made, being sure not to select ingredients which set up too rapidly.

A cluster of patterns having undercuts or other contours in such positions that it is difficult to evacuate the air from them when the sprue is in a vertical position, is grasped in a light pressure spring-jawed vise or clamp and is held so that these undercuts are upward. Sufficient of the investment material to fill the undercuts and cover the areas immediately around them is poured into them, care being taken that the pouring is done to displace the air and not entrap it at the bottom of the undercut. Still held in the same position, the cluster and its clamp are placed beneath a bell jar (or the bell jar is placed over them) and the air is evacuated from the investment. The cluster then may be set aside until the investment takes sufficient initial set to prevent its falling out when the position of the cluster is changed.

This procedure may be repeated, changing the position of the cluster, if there are several undercut areas in such positions as to give air entrapment troubles.

As soon as is practical after the preset has become adequate to prevent the material from falling out or from flowing plastically and admitting air, the cluster is placed in its flask and the heavy body of single-coat investment material is poured and vacuumed or vibrated in the ordinary way.

Variants and Options. The foregoing procedure is capable of many variants in accordance with the contours of the patterns. The variants should be studied as possible options.

The cluster sometimes can be held in proper position and dipped into the investment, rather than pouring the investment material into the undercuts. Dipping may be accompanied by a gentle rocking motion to encourage the escape of entrapped air. This procedure is both quicker and better when practical.

Special batches of investment material may be made up to have quicker presetting characteristics than the main body for filling the undercuts. This may be done by varying the ingredients, varying the temperature of the mixing water or other vehicle, or varying the mixing time, in accordance with the materials being used.

Special batches may be made of extremely fine grain refractories in order to reduce the reverse permeability within the undercuts and produce exceptionally smooth surfaces within them.

Special batches may be of material having higher thermal conductivities, thus assuring that deposition of the molten alloy either will begin at the undercuts or will not lag at them, the result being sounder metal at the undercuts. To enhance this, wires of high conductance alloys having higher melting points than the cast alloys may be placed within the undercuts as soon as the material has hardened enough to hold them. These wires, if desired, may be long enough to lead to the outer surface of the completed investment and thus to conduct heat from the undercut areas to the outer air for quicker cooling of the undercut areas. Single straight wires may be used, or patterns of wires contoured to follow the critical contours of the undercuts, a shape which is like a coiled spring having helixes to parallel the roots of the threads often being found beneficial for undercuts which are threaded. Special batches may be of specially crushable materials to act as crushable cores. In these uses ingenuity is needed.

This general type of multiple coating, then, can solve many of the problems of fragile inserts which are not incorporated in the patterns.

Selective Area Variant. Some of the foregoing variants are used when it is desired specially to control selected areas of castings where no undercuts are present.

Flask within a Flask, or "Stove Pipe" Technique. When the wall of investment is to be at least 0.50 inch thick, and sometimes when it is to be only 0.25 inch thick, the cluster is placed within its flask in the usual manner and a second and very thin flask is placed down over the cluster so that it clears the cluster uniformly and by a predetermined amount. The clearance usually is 0.125 inch but sometimes is only 0.060 inch or even 0.040 inch. This inner flask often is cut from a piece of stove pipe if the cluster is round. Otherwise it may be formed of any sheet metal.

Investment material, usually of a special mixture having very fine particles, is poured within this inner flask and is vacuumed. The bell jar is removed from the flask, and a second batch of investment material, usually one having either coarser or else random-sized particles, is poured between the inner flask and the outer to the usual level of filling. The inner flask is withdrawn, pulling it in a straight upward direction so that it does not rub against the patterns. The entire flask is vibrated to remove some of the air from the outer investment and to promote cohesion between the inner and outer investments. The vibration should not be severe.

This procedure may have two purposes. First, when a thick wall of investment is to be used so that the cooling of the castings will be slow, this technique evacuates the air from the pattern area to better advantage than if the entire thick mass were to be evacuated. Secondly, when vacuum casting is to be done and directional permeability is desired directly parallel with the sprue, or when for any other reason directional permeability is desired to be so controlled, this is an excellent control method.

Alternatives and Options. The inner investment can be made weaker and more easily crushable while the outer wall, of a stronger material, contributes the physical strength.

The inner investment sometimes is of low thermal conductance and the outer of high conductance, thus assuring that progressive deposition will be from the outer areas of the castings inward to the sprue.

The inner investment may be of high thermal conductance while the outer is of low conductance, thus assuring that if a chill or other cooling agent is placed against the exposed end of the sprue immediately after pouring the castings, the progressive deposition of metal will begin at the sprue and proceed toward the castings, and the last elements of the alloy to cool will be concentrated in the castings rather than in the sprue.

Wetting-Out Variant. The cluster is sprayed with aerosol or is sprayed or dipped in some other good wetting-out agent, after which any of the foregoing techniques and variants are used. The result is to increase the wetting out of the patterns by the investment and improve the surface character reproduction in the castings.

Ordinary Dip Coat. The cluster is carefully degreased, then sprayed with a wetting-out agent.

A special investment material, usually of the gel variety, is deposited on the cluster. Deposition may be by dipping the cluster in the investment, spraying the investment on, or painting it on. Choice among these methods is made in accordance with the ease with which air may be prevented from getting between the coat and the pattern, and in accordance with speed and cost of application.

It is important to prevent the presence of air between the coat and the pattern. Any air which is so included is not likely to be removed by subsequent vacuuming or vibrating. If dipping is done the cluster should be pushed rather than plunged into the investment, time being given for the material to take advantage of the wetting agent and displace the air. If spraying or painting is done, the application should begin at the bottom of the cluster and progress upward, thus obtaining the most favorable conditions for building the coating without air being entrapped by the material running down over the uncovered portions of the patterns. Brush painting generally is best if the material must be worked into intricate contours while being careful to entrap no air.

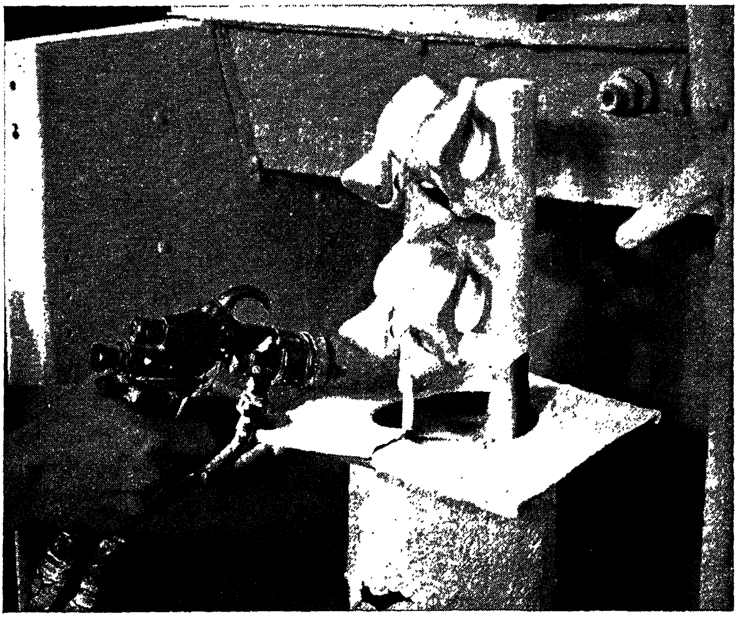


FIGURE 113. Spraying with silica after the dip coat.

Electrophoresis, by which the cluster is dipped into a liquid and the refractory particles are caused to travel to, and deposit upon, the surfaces of the patterns, is under scientific study at the time this is being written but is not ready for announcement as a commercial process. Electrodeposition, as used in spray painting, also is under study but as yet has proven too high in speed to prevent entrapment of air.

After dipping, the cluster is drained. Draining usually is not necessary after careful spraying or brush painting. The purpose is to eliminate excess material and prevent undue thickness of coating.

This original coat is of very fine particles and therefore of relatively low permeability. The thicker it is the less is its permeability. Therefore it rarely is permitted to be over 0.060 inch thick, although for applications in which extremely low reverse permeability is desired the coating may be as much as 0.1875 inch thick.

While still moist, the coating is covered with coarse-grained refractory material. The material generally preferred is Ottawa sand. The size is generally from 50 to 80 mesh, although meshes as fine as 250 have been used. The purposes are to provide an area of larger grains and therefore higher permeability immediately behind the low permeability coating, and to provide a better bonding agent for the main body of investment material. This coarse surface sometimes is known as the "back-up coat."

Since it usually is not desired that water used as a vehicle in the main body of investment shall penetrate the dip coat, a water repellant or "waterproofing agent" ordinarily is sprayed or dipped over the back-up coat. There are various "dry film" proprietary water repellants. Dimethyl silicon dichloride may be used, although it needs the use of a special container in order that its fumes may be applied in a closed container. Mineral acids may be used, also monammonium phosphate. Zinc chloride is one of the preferred agents.

The precoat now is allowed to dry and set. This may take 24 hours in still air at room temperature. In an oven which is kept well below the softening range of the pattern materials, or by other forced drying methods, the drying and setting may be accomplished in one hour.

Many of the larger houses store their precoated investments in air-conditioned chambers, the air being kept dry and at room temperature, until ready for use. Such storage may be for as long as 30 days if desired.

When the setup is complete the precoated cluster may be placed in the flask and the main body of investment applied as in a single-coat investment. Vacuuming may be used on the main body but the vacuum generally should be kept below 14 inches of mercury, or in many instances below 11 inches, to avoid fracturing the precoat. Vibrating also may be used, and generally is preferred to vacuuming. Many houses use neither vacuuming nor vibrating. The stove pipe technique may be used.

Overcoating Option. The precoat may be applied in the usual manner but kept very thin, a back-up coat applied, then a second and thinner precoat which generally is called the "overcoat." A back-up coat is also applied to the overcoat. The overcoat is waterproofed. Waterproofing is optional with the precoat, but usually is avoided since it tends to reduce the adherence of the overcoat and also is believed to be an unnecessary expense.

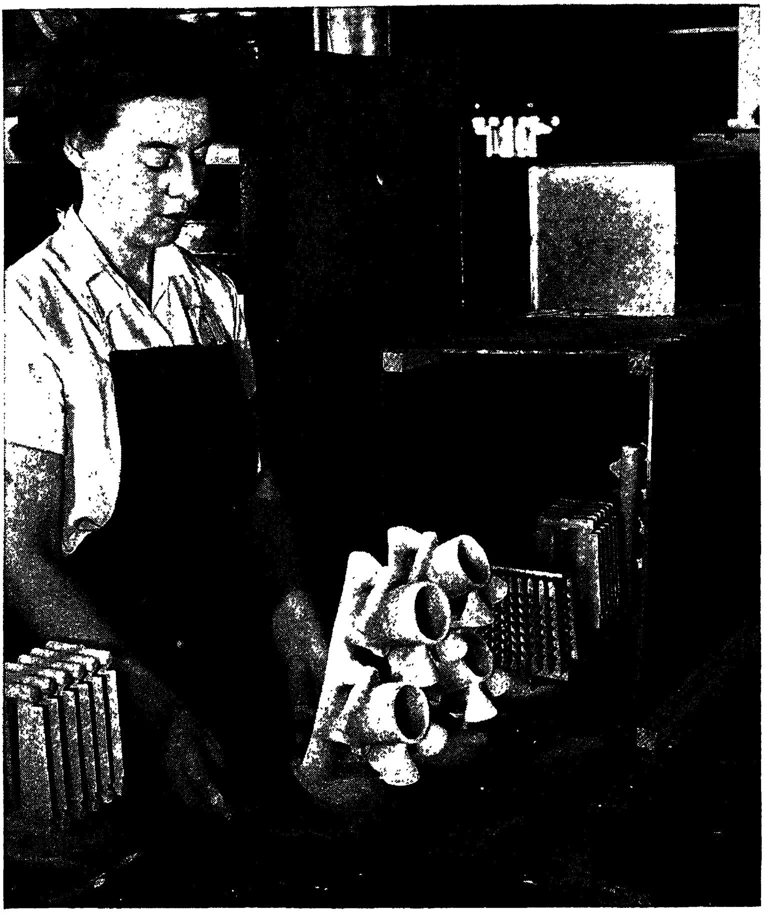


FIGURE 114. A dehumidifying tunnel drys a dip coat in 22 minutes.

Alcohol Option. If alcohol is used as the vehicle in the main body of investment, the waterproofing of the precoat, and of the overcoat if one is used, may be avoided. This is one of the main reasons for the use of alcohol and similar vehicles. Alcohol is, of course, costlier than water.

Chemical Overcoat Option. Carbon, such as powdered petroleum coke or powdered carburizing-compound, may be used either in the overcoat or in a second top coat on the overcoat. The purpose is to provide carbonaceous gases at the time of reverse permeation and prevent decarburization. The "carbon coat" should be close enough to the casting cavities so that the carbon will be gasified by the heat of the incoming metal, but not close enough so that this gasification will be complete before the castings have solidified. The placing of this coating depends upon the thicknesses of the castings and the temperature of pouring, and is largely found by trial and error.

Selecting and Procuring

As was pointed out in the early part of this chapter, cost per pound of the investment material means very little in terms of actual cost. The actual cost is that of an invested flask. And in shops which use eight or more different investment formulas the cost per invested flask of the same size in one investment can be ten times that in another.

Cost vs Scrap Loss. A cluster as it comes to the investment stage can be regarded, costswise, as a manufactured product. It has had costs for dispensable pattern material, for experiment, for depreciation and obsolescence or other "charge off" of tools, for labor, supervision, floor space, overhead. Now a cost for investing is to be added, and a cost for casting.

All of these costs must appear as cost per acceptable cast product. The higher the scrap loss of rejected castings the lower is the number of castings over which the costs may be spread and the greater is the cost per casting.

When costs to invest become high, there is a balance point at which it is more economical to reduce the investment cost and risk raising the scrap loss. Conversely, when scrap loss is high it may be better to raise the investment cost if by so doing the scrap loss can be reduced. There is no direct relationship between investment costs and scrap losses.

No formula other than "common sense" can be laid down for this matter. It is a matter of simple arithmetic for any given alloy and casting.

Formula Sensitivity. The most common investment formulas consist of about 20 per cent by weight of basic materials which the casting house buys from the investment maker and 80 per cent of fillers and vehicles which are bought in any open market. The basic materials may contain some fillers and vehicles of kinds either difficult for the casting house to blend or else necessary to make the materials shippable or workable.

Many of the final properties of the investment depend upon the fillers and vehicles which the casting house incorporates in the mixture. Surface fineness and investment permeability, for example, are largely dependent upon the fillers used.

Some basic materials are highly sensitive to the fineness and other characteristics of the fillers used, to the amounts of fillers, and to the kinds, amounts, and temperatures of vehicles. Vary the formulas even slightly and the investments "go wild," producing all sorts of unpredictable faults in the castings.

The formula-sensitive basic material may be the very best for a specific alloy or casting problem. But for most purposes it is better to have wide permissible variability in order to be able to use the fillers most immediately available and to work out formula modifications which are helpful for individual problems.

Fillers Most Commonly Used. Fillers are ceramic or refractory materials. Their grain sizes run generally from 60 to 1,100 mesh, with the great bulk from 200 to 300. They are selected for uniformity of quality, freedom from dirt or foreign matter, lightness of weight, ability to endure casting temperatures, freedom from chemical effects upon the castings, freedom from fluxing, vitrifying or other bad effects upon permeability (unless some of these effects are wanted for cyclic permeability), contributions to strength and to thermal conductance, local availability, and cost.

Fillers may be: sand (Ottawa or any good pure grade), pulverized fire brick, quartz, or gypsum. Sand (silica) is the most common.

Vehicles. Vehicles are selected for their effects upon the workability of the investment, upon setting-up characteristics and time, upon the hardness and other characteristics imparted to the basic material, upon safety hazards, and if the vehicle is other than water, upon its miscibility with any water which may be present in the investment or may be used as part of the vehicle.

Water is the most common vehicle. Among the others are: alcohol, petroleum solvents, carbon tetrachloride, dilute acids, the most common acid being hydrochloric in concentrations ranging from 5.0 to 0.5 per cent.

Fillers vs Vehicles. The fillers are selected as permitted by the maker of the basic material, the vehicles as recommended or specified by him.

Check List for Investment. A few casting houses buy raw chemicals and attempt to make their own investment materials. If the house is a division of a very large manufacturing company this may be feasible. In most instances the practice is an attempt to solve casting problems for which the proprietary brands seem inadequate. Under any other circumstances, for a casting house to compound its own basic materials is comparable to a house buying barrels of crude oil and distilling its own lubricants.

The proprietary makers have had years of experience, of trial and error, of costly research. But before selecting a proprietary maker or brand, or deciding upon what formulas to compound of basic materials plus fillers plus vehicles, the following points should be considered very carefully:

(1) Sales engineering help available from brand maker or distributor.
(2) License fees required for using the product.
(3) Sensitivities and variabilities of formulas.
(4) Pouring temperature of the alloy to be cast.
(5) Chemical effects of the investment upon the castings.
(6) Permeability obtainable: positive, differential, directional, reversed, chemical, cyclic.
(7) Strengths obtainable.
(8) Desired weaknesses obtainable.
(9) Thermal conductivities obtainable.
(10) Section thicknesses necessary.
(11) Surface qualities obtainable on castings.
(12) Flasks, types and sizes possible to use.
(13) Application methods practical.
(14) Hazards of use: silicosis, toxicity, explosive.
(15) Setting Up: minimum time, restrictions on maximum time, time effects upon mixing and applying, sensitivity to vehicle and to vehicle temperature, exothermic reaction.
(16) Melt-out problems: expansion, equipment needed, methods permissible.
(17) Air elimination methods permissible: vacuuming, vibrating, preventive.
(18) Mixing: sensitivity to methods, dry mixing, wet mixing, equipment needed, sensitivity to immediate cleaning of equipment, equipment maintenance needed.
(19) Storage problems: floor space and handling costs, hazards to material (need for care in keeping closed and dry), hazards to building (fire, explosion, chemical), hazards to personnel, storeability (hazard of deterioration if stored too long).
(20) Costs: first or "as received" cost, "as applied" cost in invested flasks costs *vs* scrap losses of castings.

Chapter 15

Casting

When fully melted out, the invested flask becomes a tool of the foundry. It differs from any other "casting mold" in that it is more controllable in its properties and in the adaptabilities of its usage. Cast molten metal does only what the investment permits and causes it to do. Precision investments, generally, can go farther in these respects than can any others.

Melting and casting practices can make some additions to the versatility of the process and can correct some troubles. But in this or any other casting process, when problems arise the best method is to go back and correct the designs of the patterns and the properties of the investments. Variations of the casting techniques can be used for controlling the metallurgy of the castings. Casting needs precision tools.

Flask Temperatures

Either as a continuous raising or lowering of its temperature from the melt-out operation, or else as a separate heating or cooling operation, the invested flask is brought to the pouring temperature. Dependent upon such factors as the alloy to be cast, the sizes and contours of the castings to be made, the number of castings per flask and their consequent distances from the sprue, the sizes and numbers of the sprues, whether or not there are risers, the gating, and the metallurgical results wanted, the flask temperature may be higher than 2000 degrees F or lower than minus 50 degrees F, or at any selected temperature which the investment material will stand.

With all of these factors, and others, and with precision investment casting handling alloys and gradations or modifications of alloys which are not commonly made into small castings, there are no rules regarding flask temperatures except the "rules of experience."

The rules of experience state:

(1) Unless metallurgical or other considerations prevent, run the metal and have the flask at the lowest practical temperatures. The metal usually is heated above its mushy range, but when extremely accurate castings are wanted the metal sometimes is poured at a temperature within its mushy range.

(2) If the castings have thin sections and are difficult to fill out, check the gating, the runners and the sprues to see if cluster design changes are needed. Also check the investment.

(3) If necessary to make changes of temperature, raise the temperature of the flask 50 degrees or so, or by 50-degree increments.

(4) Raise the pouring temperature of the alloy by 50-degree increments.

(5) Keep right on checking other factors. Work out the lowest combination of temperatures.

FIGURE 115. If the permeability is higher the flask temperature can be lower.

These rules of experience apply only so far as flask temperature can be isolated as a factor. And among them the first two are by far the most important. In nearly all instances the lower the flask and the pouring temperatures, the quicker the cooling of the castings and the better the results.

Flask Temperature vs Permeability. The most common reason for raising the flask temperature is to prevent the alloy from solidifying before it can fill out thin sections. But this filling out also is a matter of the speed with which the metal can displace the air within the cavities, and that speed is partially dependent upon the permeability of the investment. (Casting pressures also affect the speed of air displacement.)

Investment experiments should be carried out especially to see if differential and directional permeabilities cannot be made more favorable to the areas which refuse to fill out.

Flask Temperature vs Conductivity. While studying the permeability factors, experiments with investments of higher and of lower thermal conductivities may be of advantage.

An invested flask of higher conductivity may be heated to a higher temperature before pouring, and if the pouring is done before the flask has a chance to cool, the higher conductivity may result in as rapid cooling of the casting as would have been obtained in a cooler flask of lower conductivity.

An invested flask of an investment material lower in conductivity, especially if the net conductivity is reduced by thickening the investment walls and so making the investment a better insulator, sometimes may be poured at a lower temperature and the metal be prevented from freezing before it has filled out the thin sections. The flasks for this should be thin-walled.

Flask Temperature vs Strength. The cooling of metal is a matter of time *vs* conductivity. Sometimes, and especially in vacuum casting, the metal can be forced into the investment cavities so rapidly that it fills out the thin sections before it has time to lose its liquidity. But this is impossible if the physical shock, the temperature shock, or the erosive ability of the metal can spoil the investment when the metal is moving at the necessary velocity. Experiments with stronger investments may permit higher speed casting into a lower temperature investment.

Some alloys gain rapidly in viscosities with reductions of temperatures. With stronger investments higher casting pressures sometimes may be able to overcome the increasing viscosities of the cooling metals, and the need to raise flask temperature in order to reduce viscosities may be modified.

Flask Temperature vs Specific Heat. The specific heats of metals, of course, affect their resistances to temperature changes. Therefore an alloy high in specific heat will maintain its liquidity longer, all other factors being equal, and may be cast into a flask of lower temperature.

The similar effects of specific heats of investment materials have not been analyzed to sufficient extent to warrant any more than a general statement that an investment higher in specific heat should permit a lower flask temperature.

Flask Temperature vs Thermal Conductivity of Metal. Since the thermal conductivity of the alloy almost always is higher than that of the flask, it follows that an alloy high in conductivity will tend to keep itself liquid by the flow of heat from its liquid areas to its solidifying ones. For alloys high in conductivity, the flask temperature may be lower without trouble developing in the filling out of thin sections.

In fact, it is for alloy steels of the lowest or "most sluggish" thermal conductivities that flask temperatures generally are highest, and it is for high heat conductance alloys such as aluminums that flask temperatures are carried as low as minus 50 degrees F.

How to Cool a Flask for Low-Temperature Pouring.

(1) Melt out by the boiling water plus vacuum technique, or by applying vacuum to the sprue button while the flask is in saturated steam at 15- to 25-psi pressure.

(2) Complete the melt out at a temperature below the inversion range of the investment, usually at a temperature no higher than 600 degrees F.

(3) Cool in an oven, permitting temperature to drop no more than 100 degrees an hour to room temperature. *Make sure that the air supplied to the oven is dry.*

(4) Pack in Dry Ice or submit to moisture-free refrigeration means. The minimum time is unknown but is believed to be at least six hours.

Flask Temperatures vs Segregation. Flask temperatures sometimes must be raised to prevent too rapid deposition of the alloy elements which are highest in their solidifying ranges, and consequent undesirable segregation.

Flask temperature sometimes is lowered to cause rapid deposition of the elements which are highest in their solidifying ranges and thus to "rob the sprue" by segregating within the castings the most valuable elements of the melt.

Check List for Flask Temperatures. The temperature differential between the pouring temperature of the alloy and the temperature of the flask commonly is called "temperature drop to flask." For speed and convenience of use a check list of points to consider when establishing that temperature drop, and hence when selecting the flask temperature, may be helpful if the casting house amplifies the list with further factors peculiar to its own practices. The basic check list includes:

(1) Fusing or vitrifying of investment elements. Avoid temperatures which will cause this unless it is deliberately desired for the control of permeability.

(2) Avoid temperatures immediately below the inversion ranges of investment materials.

(3) Permeability of investment material.

(4) Thermal conductivity of invested flask.

(5) Strength of invested flask.

(6) Velocity of entering metal.

(7) Viscosity of entering metal.

(8) Predicted increase of viscosity before cavities are filled.

(9) Specific heats of entering metal and of investment.

(10) Segregation problems of alloy elements.

(11) Casting method. The higher the pressure the lower may be the flask temperature.

(12) Effects of vacuum if used when casting.

(13) Number of temperature dropping process steps between melting and casting.

(14) Metallurgical effects.

(15) Thinness of sections to be cast.

Casting Methods

The methods in use for casting or pouring the molten metal into the invested flasks include gravity, gravity-vacuum, low pressure, pressure-vacuum, high pressure, axial centrifugal, radial centrifugal, cyclic centrifugal, centrifugal-vacuum, and vacuum-pressure.

The method selected may have a strong influence upon the temperature needed for the flasks and upon the amounts and kinds of permeability required in the investments.

Vacuum Systems. Vacuum may be applied to any flask for any casting method. It rarely is applied to ordinary types of centrifugal casting in this industry; the mechanical difficulties are too great.

The effect of vacuum in most instances is to increase the permeability of the investment. There is some decrease in the amount of air within the casting cavities. But that decrease cannot take place until the sprue entrance has been sealed off. And in most instances the sprue entrance or "down gate" is open until the pouring of the molten metal seals it.

The most common method of applying vacuum is:

(1) A piece of porous asbestos paper is cut to a size which will clear by 4 inches all sides of the part of the flask to which it will be applied. This paper is moistened. It must be kept moist so long as it is in contact with the flask.

(2) The ladle or other pouring means is made ready to pour. All procedures must be carried out rapidly; therefore all devices must be ready.

(3) The flask is placed upon the paper or the paper upon the flask, whichever may more conveniently be done while providing space for the vacuum cup to be applied to the desired area of the paper.

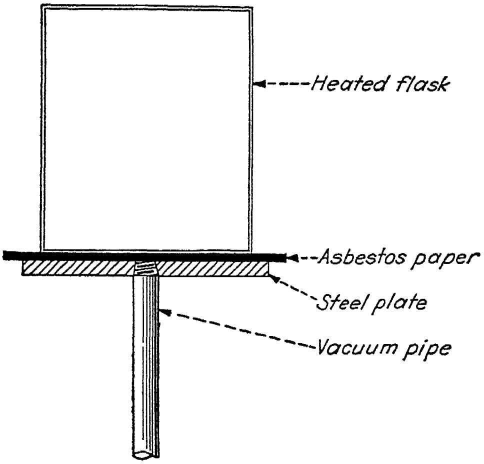


FIGURE 116. Simplest method for applying vacuum to flask.

(4) Additional moisture is applied, if necessary, to the edges of the paper which clear the flask. The paper must be kept moist for two reasons. One is that the moisture reduces the flow of air between the flask and the paper and thus causes the vacuum to be applied through the paper to the flask rather than merely drawing air which leaks lengthwise of the paper. The other reason is that ordinary asbestos paper is not designed to withstand temperatures of over 1000 degrees F, and the flask is likely to be at higher temperature than this. The paper must be moist, not wet, since the application of a large amount of cold water might crack the flask before the pouring could begin.

(5) Pouring begins as quickly as possible after the paper has been applied to the flask.

(6) The vacuum cup is applied to the selected area of the paper as instantaneously as is possible after the pouring has begun, and the vacuum valves are opened wide. A vacuum tank is preferable to a vacuum pump alone for this purpose since the pump alone cannot, as a rule, get the vacuum going quickly enough.

The vacuum cup sometimes is applied slightly before the pouring is begun. But there is a danger in this that cold air may be drawn into the casting cavities with resultant thermal shock which is almost certain to result in spalling of the cavity walls when the molten metal is poured.

(7) The vacuum is continued for a time period during which the metals solidify, and in some instances during which they also cool below their rapid oxidation temperatures. This time period is found by trial and error. The vacuum should be continued, in most instances, at least until the exposed end of the sprue is observed to have frozen. Time periods in common use range from a few seconds to ten minutes.

Application Point and Time Period. In estimating the first application points of the vacuum cup (or cups) for the beginning of trial and error experiments to find the best points, and also in making the first estimates of time duration of application, consideration should be given to the nature of a vacuum and the probable events when vacuum is applied to the flask.

Vacuum consists of an area of higher potential kinetic force or energy attempting to move to an area of lower potential. The higher pressure in the flask attempts to move into the low pressure in the vacuum tank.

Neglecting any effect of lack of perfection of the vacuum in the tank (it is close enough to "perfect" so it suits its purpose), the total force causing the air to move into the vacuum tank is the normal atmospheric pressure (about 15 psi) plus any pressure exerted by the pushing of the molten metal against the air within the investment cavities.

The atmosphere also is trying to enter at the point of application of the vacuum cup, and by the methods ordinarily used there will be considerable leakage around the cup. The net effect of this leakage depends upon the size of hose or pipes leading to the vacuum tank and the overall ability of the vacuum tank and system to overcome the leakage. For a given vacuum at the tank, usually 29.75 inches of mecury, the bigger the tank and other members of the system the better the overcoming of a given amount of leakage.

The leakage will produce at the cup an area of pressure higher than that at the tank. The force which will move the air from the cavities into the cup will be dependent somewhat, but far from altogether, upon the pressure differences between the casting cavities and the interior of the cup. This pressure difference, for most flasks, has not even been calculated at casting temperatures and would be very difficult to measure.

Also leaking into the cup is air which comes through the permeability of the flask but from the outsides of the flask and not from the cavities. This increases the difficulty of measuring what goes on inside the cavities.

As measured at room temperature, and with the vacuum applied by the simple method described above, it is very difficult to obtain a vacuum of more than 4 inches of mercury within the casting cavities. This measurement is only an indication of the conditions which exist when the cavities are at high temperature and still higher temperature molten metal is pushing against the air within them. But it would not take very much additional pressure applied to the metal itself to obtain the same casting pressure effects as would be delivered by that amount of vacuum. And since increases of pressure do not yield the same results as application of vacuum, the effects of the vacuum must be other than those of added pressure.

The air can travel out of the cavities only as rapidly as its critical pressure will cause it to, and the passages and their orifices will permit. See page 271.

The effects of the vacuum upon differential permeability and directional permeability can be great. As the air is partially exhausted from the investment passages nearest the vacuum cup, it will begin to exhaust from the passages directly connected with them. There must, therefore, be a series of areas of successively higher pressures, lowest at the cup and highest at the cavities. With every reduction of pressure the chances of back pressure building up until it equals critical pressure will become less. And the air will always move from an area of higher pressure into one of lower. Consequently, the direction in which the air will tend to move will no longer be a sole matter of the directional permeability built into the investment but will be the result of a combination of that directional permeability and the effects of the vacuum. And since the effects of the vacuum will be greatest in the immediate vicinity of the vacuum cup, the closer the air gets to the vacuum cup the greater will be the effect of the vacuum and the less the effect of the directional permeability.

When the casting begins to solidify and reverse permeability to set in, the permeating air has to come from somewhere. Its natural path of travel is along the lines of directional permeability. But if the vacuum is still at work, no air can come from the direction of the vacuum cup until the vacuum created by the shrinkage of the castings becomes sufficient to overcome that applied by the cup, and even then the air return will be slow since there will be very little air supply in the immediate vicinity of the castings.

Most houses which have experimented with vacuum have found that it has its most beneficial effects if the cup is placed directly in line with the path in which directional or area permeability has been giving trouble. And that path most commonly is directly in line with the axis of the sprue. Accordingly, the first trial points for the application of the vacuum cup or cups should be directly in line with the areas at which directional permeability has been giving trouble. Those areas are detected by the existence of pitting or other surface troubles on the castings, and by failure of the cast metal to fill out fine sections.

Other trial points exist when the present directional permeability is satisfactory, but it is desired to create other directional effects. A cup can be "aimed" at a specific area of a cavity.

When flasks are rectangular or oblong and clusters are comb-shaped, trouble may be had with the castings at the ends of the comb. Vacuum cups may be applied to the ends of the flask and aimed at the trouble spots.

The duration of the application of vacuum depends upon the time period over which it is desired to control reverse permeability. This differs with alloys. Some alloys are not adversely affected by reverse permeability, their surfaces not being oxidized to any greater depths than will be removed by the normal methods of cleaning up the castings. The first experimental duration should be short. Upon later trials the period may be lengthened until either the desired results are obtained or it is demonstrated that the vacuum cannot yield them in the present investment.

Experiments with vacuums quite commonly lead to changes made in investment materials and methods in order to secure more desirable kinds and amounts of permeabilities.

Vacuum vs Flask Temperature. Since vacuum affects permeability and permeability is one of the determinants of flask temperature, the use of vacuum often permits lower flask temperatures. In turn, lower temperatures facilitate the use of vacuum.

Some Probable Effects. To anyone who wishes to search the literature or do experimental research on vacuum as it affects the permeabilities of hot flasks, these lines of thought are suggested:

(1) The heat energy gained by compression of the air and by contact with the hot metal is enthalpy.

(2) As the air is forced through fine orifices the action is largely a

throttling one, and throttling is generally considered to entail no net loss of *enthalpy*.

(3) If no vacuum is applied, to the extent that air from one tiny chamber of the permeability must force air from another, the moving of the air is accomplished by loss of heat energy and is *adiabatic*.

(4) If vacuum is applied, to the extent that the vacuum is effective, the air is moved by an external force and the air movement approaches the isothermal. The air escapes with more of its heat energy intact. This must be considered when planning the vacuum equipment.

Vacuum Methods. The entire subject of applying vacuum to flasks will advance rapidly when the research departments of the asbestos and other high temperature material companies evolve resilient (flexible) materials which can be placed directly against the flasks to act as vacuum cups. In the meantime several methods are in use or under experiment by the casting houses. Among them are:

(1) A flat piece of steel slightly larger in outside diameter than the flask is drilled through at its center and is threaded with a standard pipe thread. A pipe coupling leading to a flexible metal hose is attached by the thread, the hose in turn leading to the vacuum tank or pump. This flat steel piece becomes the vacuum cup to be placed against the asbestos sheet in the simplified method described above.

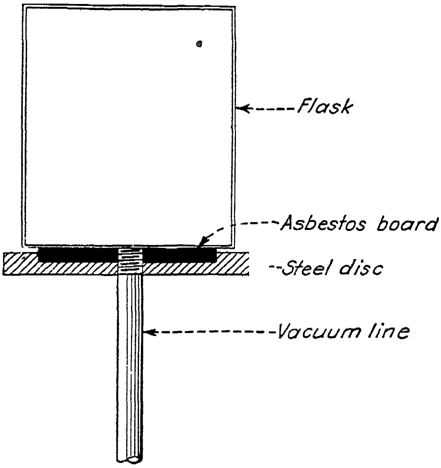


FIGURE 117. Recessed disc vacuum method.

(2) A high grade asbestos board suitable for temperatures to 1700 degrees F over extremely short time periods is cut to a disc shape (or other

shape) about 0.250 inch smaller on each dimension than the bottom of the flask. A flat piece of steel is recessed to receive this piece, the recess being deep enough so that when laid in the recess the flat side of the asbestos board will protrude about 0.030 inch. The steel is drilled and threaded at the center of the recess as in (1) above. The asbestos board is drilled at its center to match the hole through the steel. The asbestos board is moistened thoroughly before being placed in contact with the

(3) If the vacuum is to be applied to other than a flat contour of the flask the steel may be selected to a contour (cutting the piece from the wall of a tube, for example) or may be machined to fit the flask contour, for methods (1) and (2).

(4) Instead of the piece of steel a recessed casting is used, the recess being a cored area which does not connect in any way with the vacuum. Cooling water is flowed continuously through the cored area to relieve the temperature burden on the asbestos sheet or board. Otherwise the procedure is as in (1) or (2).

(5) When the investment is strong enough so that it may be melted out and heated up without the use of a flask, a steel shell is so prepared that its inside dimensions are a close fit to the outsides of the flask. The shell is a cup, having its bottom drilled, tapped, and if necessary reinforced, to receive the vacuum hose. The wall of the shell comes to a predetermined height on the flask, usually very close to the top of the flask when the flask is within the cup.

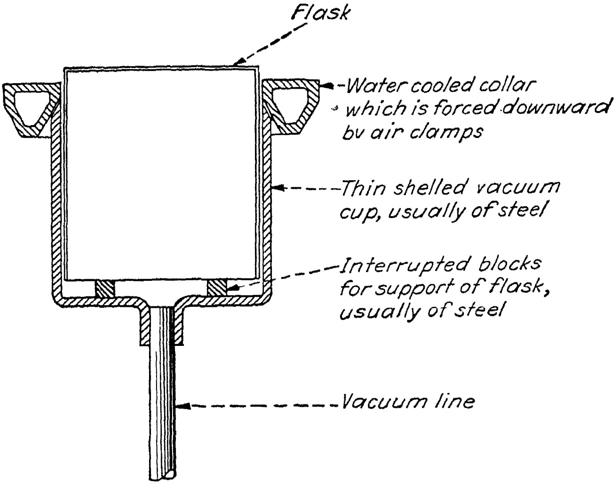

Flask
Water cooled collar which is forced downward by air clamps
Thin shelled vacuum cup, usually of steel
Interrupted blocks for support of flask, usually of steel
Vacuum line

FIGURE 118. Tapered-edge shell application for vacuum.

The top of the wall is machined down to a very narrow taper, the thin edge of the taper being toward the flask. A collar is fashioned with a female taper to fit this male one, the collar being hollow and provided with water inlet and outlet connections and hoses.

When the flask and furnace are ready for pouring, the vacuum is started slightly through the chamber so as to overcome the immediate heat expansion of air when the flask is inserted. The flask is carefully but quickly inserted into the chamber. The collar is placed over the taper, the cooling water immediately started flowing through the collar, and quick action air clamps are applied to force the collar down continuously on the taper.

The metal is poured. The effect of this heat is to expand the chamber at all areas except the one at which the cold collar is holding the taper. The expansion or "bellying" of the metal below the collar turns the collar in slightly, and gives it a "digging in" effect. The vacuum valves are opened wide.

Static Casting. Static casting is the feeding of the molten metal by the force of gravity alone. During the early days of precision investment casting static pouring was considered impossible to the process. Nearly all investments in those days had plaster of Paris binders. The difficulties were with the permeabilities of investments made with that binder. Many of the modern proprietary brand binders permit permeabilities which are highly favorable to static casting. And increasing amounts of static casting are being done.

Static casting has three general factors in its favor. It requires the least equipment. It applies only gentle forces to the alloy and the investment. And it permits the use of risers, especially of blind risers.

Sprues, Runners and Gates. Since the force of static casting is very little, the sprues, runners and gates must be generous in capacities. Much depends upon the specific gravity and the liquidity of the alloy. The higher these factors the less may be the cubical capacities of the passages.

Since the metal ordinarily freezes first at the tip of the sprue and then progressively downwards, the metal below the tip may remain free to flow for some time after the tip solidifies. That continued flow is molten at first, and then plastic. When plastic, its flow direction is contrary to the forces of freezing contraction and can result in bad metallurgical structure where the strains occur. These strains should be confined to the sprue and runners.

At the same time, freezing undoubtedly has begun at the extremities of the casting cavities. As these areas contract and as they form dendrites, metal must continue to feed in order to fill the interdendritic channels and prevent dendritic unsoundnesses in the castings. This feed comes by the continuous flow from the sprue through the runners. But there can come a point at which enough of the sprue and of the castings can have solidified so that some areas of the castings can begin to flow plastically or can be affected by any plastic flow from the runners.

Therefore, the most successful general practice is to have generous-sized sprues and gates with smaller capacities of runners. The runners then tend to freeze and shut off plastic flow from the sprue. This practice tends to make the clusters for static casting somewhat different in design than those for other casting methods.

Permeabilities. Since the force of the metal pushing the air out of the cavities is low, the permeability should be high. This militates somewhat, but not severely, against the use of very fine-grained precoats for extremely fine surfaces.

Directional permeability is more of a problem. If the flask is invested, as is normal, with its sprue tip in a downward position, the directional permeability created while applying the investment will be upward from the sprue tip. When the position of the flask is reversed so that the sprue is upward to receive the molten metal, the main direction of permeability will be downward. But heated air forced from the cavities does not travel downward unless forced to do so. The air will reverse its direction within the flask and will travel upward if any channels are open to it. The value of permeability downward from the sprue is least in static casting. But the value of upward permeability is high.

Some of the most successful investments for static casting are "stove pipe" types in which the outer shells contain high percentages of coarse refractory particles. The sprues of these are made 0.50 inch longer than would otherwise be necessary. After the investment material has set up, the sprue ends of the investment are sawed off to a depth of 0.50 inch, the saw blade going straight across, thus removing the extra length of sprue material also. The result of the sawing is to remove any relatively impermeable skin which may have formed on the sprue end of the investment and thus to permit the highest permeability in an upward direction.

Static investments also are successful if made in rectangular shapes and of materials strong enough to need no flasks when being melted out and cast. The flask is lined with extra thicknesses of porous asbestos paper so that the vacuum and the vibration can provide maximum permeabilities toward the sides of the investments. The flask and paper are removed after the material has set up, and the flat surfaces are sawed or are wire brushed to remove any impermeable skin which may have formed during the setting up.

Flask Temperatures. Since the molten metal may flow somewhat slowly and may apply little force against the air in thin sections, the flask temperatures for temperature-sluggish alloys need to be higher than for other techniques of casting. But if the molten alloys are high in thermal conductivities, this requirement does not apply. Intensely cold molds for aluminum and other high conductance alloys commonly are gravity poured.

Risers. Blind risers are more successful for gravity casting than for most other casting methods. The usual criticism of a blind riser is that it cannot feed because the vacuum created by its loss of dimensions while feeding and while shrinking keeps the metal from flowing downward. But with directional and area permeability always existing in an investment the warmed air from the casting cavities tends to move upward to the top of the riser, and the shrinkage of the riser gives that air a natural gathering place and breaks the vacuum.

Blind risers in this way not only solve problems of feeding the castings but also reduce the permeability troubles. Risers are most successful, generally, for high conductance alloys in which all of the heat in the poured metal tends to keep the riser molten and feeding.

Gravity-Vacuum. If the air in the cavities remained at a constant temperature, a reduction by vacuum of one pound in that pressure would have nearly the same effect as an increase of one pound in the atmospheric pressure in forcing the metal into the flask. But since the entering metal is hotter than the air in the cavities and creates an immediate increase of heat-pressure of that air, the immediate effect of the partial vacuum upon the back pressure within the cavities is unknown, but probably is less than generally is calculated. This statement is based upon the fact that the "calculated" results rarely are approached.

The vacuum does have a decided effect of overcoming the handicaps of downward directional permeability. It gets more air out of the investment instead of all the air attempting to fight its way upward. And as rapidly as the effects of the vacuum can be applied, the metal does flow more rapidly and completely into the cavities.

Risers. Risers are just as practical with gravity-vacuum as with plain gravity casting. Enough air goes upward within the investment to permit them to function. And some air permeates from the sides of the investment to displace a portion of that removed by the vacuum.

Vacuum Directions. The vacuum cup usually is most beneficial if aimed directly at the axis of the sprue. But when upward directional permeability has been provided as described under "gravity casting," the vacuum may be applied in an upward direction, especially if the flask is rectangular with the sprue in the middle and two vacuum cups may be placed, one on each side of the sprue and well toward the ends of the investment.

Flask Temperature. In theory the flask temperature should be permitted to be a little lower than for plain gravity casting. But in actual practice the permissible temperature difference rarely is significant.

Low Pressure and Pressure-Vacuum. Low pressure casting applies an air pressure generally of 4 to 6 psi and sometimes up to 30 psi to the molten metal at the sprue opening. Pressures of over 50 psi usually are called "high" although there is no valid arbitrary dividing line between low and high. There seem to be very few intermediate pressures in use excepting as obtained by centrifugal force, the common ranges of direct pressures going up to about 8 psi and then jumping clear to about 400 psi and over.

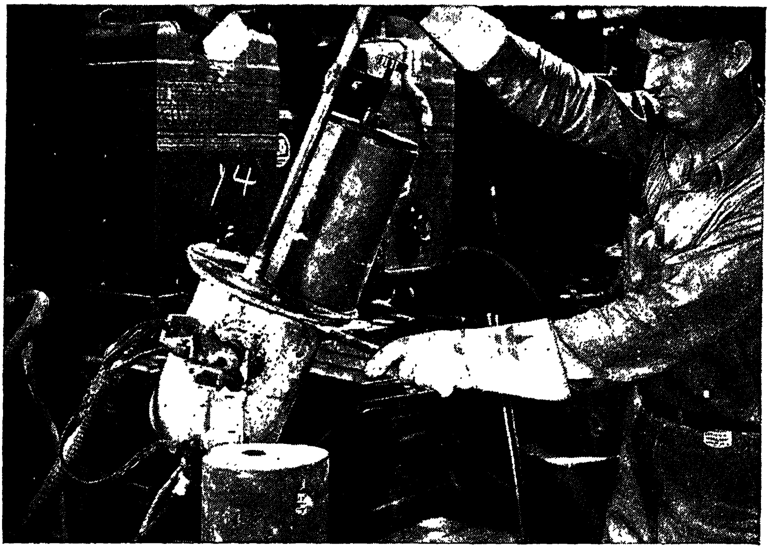


FIGURE 119. Flask in position at low-pressure furnace. The furnace is inverted for pouring.

The actual effects depend upon the cross-sectional area of the sprue tip as well as upon pounds of air pressure exerted. Therefore, by slight variations in sprue tip or "button" diameter, it is easy to vary the pressure exerted by the molten metal against the air in the cavities without changing the furnace pressure.

The air under pressure within a closed chamber and pressing against the sprue end has something of an insulating effect and delays the freezing of the sprue tip somewhat. As this extra pressure on the metal forces the air out of the cavities the critical pressures within the permeable passages become higher, but so do the rapidities with which back pressures gather to oppose them. Therefore the effects of differential permeabilities are highly important, and with them the effects of the directional permeabilities to which the differential permeabilities lead. Low pressure casting appears to be at its best when the patterns are dip coated in very fine-grained and relatively impermeable but thin sectioned investment areas which are backed by much larger grained, heavily vibrated, highly permeable, main investment bodies. The metal pressure forces the air out through fine permeability passages, and reverse permeability is able to bring very little of it back to damage the casting.

Pressure on the sprue tip tends to force it downward as it freezes and contracts. Plasticity in the cooling sprue, then, tends to be compacted rather than to be distended, unless this effect is not wanted and the sprue button is tapered or otherwise so constructed that it cannot move after freezing. When this last is done, pressure casting ceases to be "pressure" upon the freezing of the sprue tip and thereafter becomes gravity casting. The reason for ceasing the pressure in this way is to take advantage of the generous sprue and gate but smaller runner technique which permits the runner to freeze before the casting and confines the worst shrink effects to the gate and runner areas.

Risers. Risers generally are not practical with pressure casting, the pressure tending to keep them from feeding. They sometimes can be used if gated generously enough so they will feed after the pressure has been shut off. Attempts have been made to give the blind risers direct connections with the sprue as well as with the cavities, thus making the pressures on them two-directional and equal and permitting feeding, but these stratagems rarely are reported as working out in practice.

Flask Temperatures. Since the pressure forces the metal into the cavities, the flask temperatures definitely may be lower for pressure than for gravity casting. In fact, one of the principal uses for low pressure casting is for alloys so viscous in their flow characteristics at their best pouring temperatures and so sluggish in their thermal conductivities that if gravity cast the flask temperatures would have to be almost impossibly high.

Pressure-Vacuum. Since low pressure casting largely is used in multiple coat investments having first coats of relatively low permeabilities, the air tends to leave those first coats at relatively low velocities and effective pressures. Therefore the air is not pushed rapidly away from the vicinities of the first coats, and tends to follow the directional and the area permeabilities of the heavier coatings. But since the pressure commonly is applied in a downward direction so as to add the weight of the metal to that of the pressure in filling the cavities, the tendency of the air is to travel in an upward direction or to linger under pressure within the investment. Vacuum applied in line with the directional permeability tends to relieve this condition and is of high value in pressure casting.

The methods and reasons for applying vacuum are substantially the same as those described for gravity casting.

High-Pressure Casting. There are some alloys, especially some of those intended to resist high temperatures, which are so high in their solidification temperatures that they must be poured into flasks at the highest temperatures the investments will stand and then must be cast under heavy pressures in order to fill the flasks quickly. The methods of handling these alloys are little publicized, and are of little interest except to houses which specialize in the high temperature alloy field.

High pressures sometimes are used for their compacting effects upon the alloys. The methods generally are those of vacuum-pressure (not pressure-vacuum) and are described on page 336.

The methods used for direct high pressure are cyclic modifications of pressure-vacuum. It would be generally impractical to release molten metal under 400-psi pressure into an investment. The shock percussion with which the metal would strike, and the erosive effects upon the cavity walls would be too damaging to the investment. And any too high-pressure high-speed injection of molten metal tends to compress the air and to add the energy of high temperature to the air to such a degree that either the metal comes flying back out of the sprue or else minor blastings of the investment wall take place at all areas where differential permeability places a large channel directly behind a small one. The stress differentials between the areas where the metal originally strikes and the surfaces not yet impinged by it also are higher than the investment can stand.

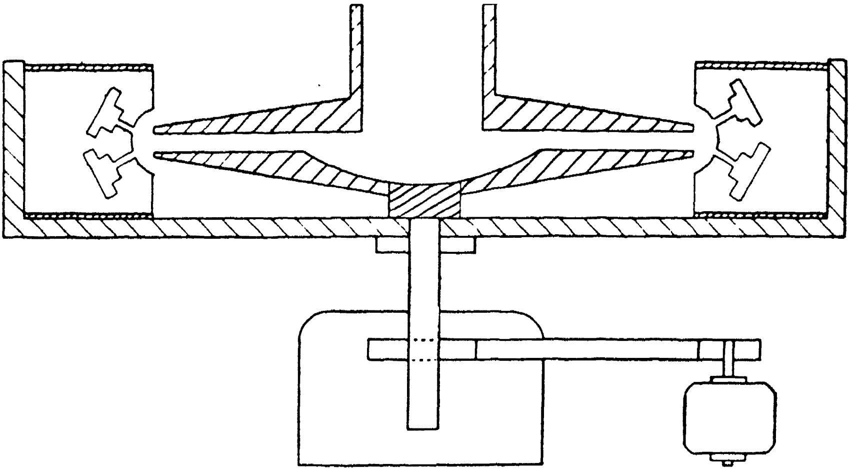
The high-pressure injection, therefore, begins as a low-pressure one until the cavities are very nearly filled and the air is almost completely out of them. The pressure on the metal is stepped up, but the stepping up is a steadily increasing push and is not a hammer blow. Obviously, the flask and the investment must be strong enough to take the pressure, and must be mounted within a steel shield so that if a weak area fractures under the pressure, personnel will not be injured by the flying fragments.

High Pressures vs Internal Welding. It is widely believed that high pressure casting may have a healing or "internal welding" effect upon extremely fine fissures or dendritic cracks which may form within the cast metal, the effect being similar to those obtained by rolling and other wrought processes. An opposite school holds that precision investment casting can obtain these same values by its close control of progressive deposition of metal, and that high pressure tends to cause gases and "dirts" to segregate and become weakening to the castings while low pressure tends to distribute them so finely and widely that they have no weakening effects. At the time of this writing, experimental work has not gone far enough to produce any conclusive evidence as to what alloys are favorably affected by high pressures.

Centrifugal Casting. In its various forms, centrifugal casting is subject to permeability phenomena which never have been explained. It is known that air is in some way subject to centrifugal forces. This has been demonstrated in the Hilsch tube. But the reasons why the Hilsch tube works are not known even in scientific theory.

A Hilsch tube has an internal spiral, two ends with very small openings, a separate nozzle at one end for the admission of compressed air. The air strikes the spiral and is whirled rapidly. The whirling separates the air into cold and hot areas. The cold area goes to the bottom of the spiral and therefore cold air comes out of the opening at the nozzle end. The hot area goes to the outside of the spiral and is carried along the tube; therefore hot air comes out of the other end. Temperature differences as great as 164 degrees F between the ends have been obtained and far greater differences are predictable. For further information reference should be made to the literature.

From the viewpoint of the casting house it is unimportant whether the Hilsch tube effect does or does not exist within a flask or whether that effect is any greater in a centrifugally cast flask than in a direct pressure cast one. The important point is that air creates some strange permeability problems in centrifugal casting and that those problems are solvable by experiments with changes in permeabilities rather than by changing the temperatures of the alloys or the positions of the gates, except as temperatures and gates affect the expulsion of the air and therefore the functioning of the permeable passages.



(*Courtesy Whip-Mix Corp., Louisville, Ky.*)

FIGURE 120. Schematic diagram of double-arm axis centrifugal casting machine.

Directional Permeability Effect. By every theory of centrifugal force the molten metal, or high percentages of it, should go first to the farthest limits of the centrifugal radius and should fill the cavities backward toward the centrifugal axis. In axial centrifugal casting (the centrifugal radius is parallel to, or axial with, the main axis of the sprue) the metal therefore would go first to the bottom of the flask cavity, would expel the air at that area, and would compel the air to escape by the paths of least resistance which would be outward through the permeability and sideways into casting cavities. As the metal filled the cavities, it would find each successive one higher in the quantity and pressure of the air to be displaced.

Experimental evidence shows that the reverse often happens. The air tends to follow the direction of centrifugal force through the permeable passages in the investment as well as within the cavities, to gather under high energy and compression within the permeable area immediately adjacent to the bottom of the main cavity, and to fight the incoming metal at this point where, by all theory, the air pressure should be least. The action seems to increase in severity with increases in centrifugal force, and sometimes is so severe as to eject large proportions of the molten metal from the flask.

This air pressure is directly opposite to the directional permeability natural to a vacuumed flask. Attempts to increase that directional permeability rarely seem to overcome the trouble and have been known to weaken the bottom of the investment so that it ruptured and the metal went on through it. Thick bottoms on investments, with resultant reductions of natural directional permeability, often cure the trouble.

"Stove pipe" types of investments, with the high permeabilities of their outer shells and the tendency of the permeabilities to be universal-directional, have cured this air pressure concentration problem even when extremely high centrifugal force was employed. The answer seems to be in a change in the direction of permeability, a change usually found by trial and error.

Area Permeability Problem. The imprisoned warm air which does not escape by the directional permeability tends to rise within the cavities and through the permeable area of the investment and to gather in the upward cavities and in the permeability areas immediately adjacent to them. This effect exists in all casting methods but seems to be greatest in centrifugal casting. The air in those areas seems, by experimental evidence, to be under greater compression than that in the lower cavities. But since gravity will cause the lower cavities to tend to fill before the upper ones, the extra pressure in the upper cavities could be explained by the fact that the air in them has gathered more heat energy from the incoming molten metal.

In many instances the most economical plan is to anticipate that the upper castings will be faulty and to permit them to act as risers, thus producing some scrap castings but obtaining better castings from the lower cavities.

Multiple-coat investments having high permeability differentials between their inner and outer coatings often can cure this trouble, the air then tending to go upward through the highly permeable outer coating rather than to gather under high energy and compression in the vicinity of the upper cavities. "Stove pipe" investments have been especially successful.

Peculiarities of Centrifugal Casting. Since the centrifugal force varies as the square of the distance from the centrifugal axis to the centrifugal periphery, and also for any radius varies as the square of the rotational speed, wide but controllable variations in the pressure applied can be made by changing the position of the flask along the radial arm, changing the speed in rpm, or changing both. Thus the pressures and velocities with which the metal enters the cavities are more readily variable by this than by any other casting method. Centrifugal casting is highly adaptable.

The centrifugal force continues to operate and to cause dimensional and positional changes in the metals so long as any part of the metal continues to be liquid or plastic enough to flow under the applied force. Thus the continued feeding of metal is independent of whether or not the sprue tip has frozen in advance of the metal within the runners and cavities. This feature can have highly desirable effects, and highly undesirable ones.

Centrifugal force acts upon elements of varying densities within the alloys so long as the alloys remain liquid, the denser (heavier for the same unit volume) elements tending to concentrate partially, but rarely completely, at the points where the greatest centrifugal force exists. Thus centrifugal casting can make use of phoresis to produce castings having differing alloy ingredients and differing strength characteristics at desired areas. But this tendency also can be detrimental enough to make some alloys impractical to be cast for some purposes.

Centrifugal casting can cause the cast metal to form striations tangential to the circumference of rotation and thus can produce directional strengths in castings to an extent not known to be obtainable by other casting methods.

Flask Temperatures. Flask temperatures generally can be lower for centrifugal than for other methods of casting the same alloys. Pressure and velocity both can be increased by centrifugal force in order to permit lowering the flask temperatures.

Flask Shapes. Most of the flasks used for centrifugal casting are cylindrical, for no other reason than that tradition makes them so. Gains may be made by the use of rectangular flasks, the principal gains being those of a "comb-shaped" cluster which will permit all casting cavities to be below the level of the sprue and thus will get rid of the permeability problems of the upper cavities, and those general to the superior (for some shapes of castings) metallurgical control and permeability control features of the rectangular flask.

Axial Centrifugal. In an axial centrifugal machine the main axis of the sprue is parallel to the radius or "arm" of centrifugal force. This arm may rotate in a horizontal or in a vertical plane. Rotation also could be in planes other than these, and it would be possible to make the plane variable during the rotation, but no machines making use of these features are known to be in use.

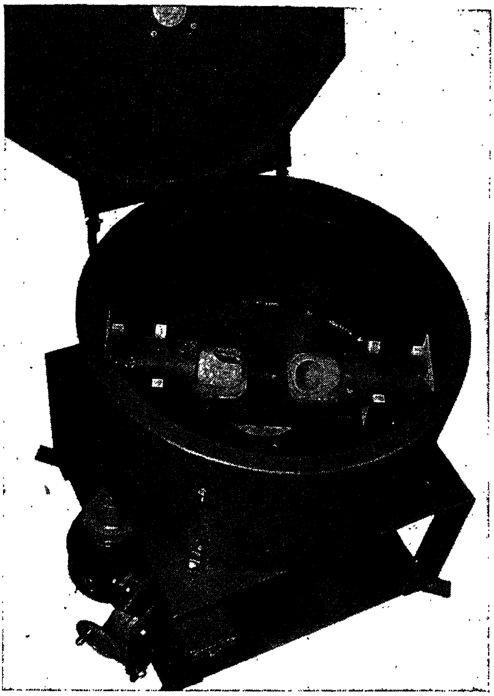


FIGURE 121. Double-arm, mouth-to-mouth centrifugal casting machine.

(Courtesy Ecco High Frequency Co., North Bergen, N. Y.)

The most common error in regard to axial centrifugal machines is to assume that the only significant effect of centrifugal force is that of pressure and that the pressures obtained are directly comparable in their effects to those of direct pressure casting machines. The reasons why this assumption is incorrect have been discussed in the foregoing general analysis of centrifugal casting. The most common bad result of this assumption is almost endless experimentation with gating as a means of making the process work when the real problems are those of directional and area permeability.

Upper and Lower Cavities, Flask Marking. A great many shops have observed that when the plane of rotation is horizontal the upward cavities ("upward" meaning away from the earth, as a roof is upward from a basement) are likely to produce faulty castings. When this condition is severe, some flasks will "go wild," distribute the faults over larger numbers and areas of castings. The reason is likely to be that the flask which produced the fewest faulty castings was in a position favorable for confining the permeability difficulties to the smallest number of cavities. The immediate remedy often is to mark each flask at the time the sprue is inserted for investing, the mark to be one which will not be obliterated during the melting out and heating up, the mark to indicate the surface area of the flask which is to be upward when the flask is mounted in the casting machine. The final remedy is to correct the permeability of the investment.

Metal Temperatures. Centrifugal machines are of two general types. In the most common type the molten metal is poured into a crucible or chamber at the centrifugal axis. There may be more than one arm in order to fill more than one flask at a single pouring. The metal then may be subject to several temperature drops. In an extreme condition those drops would be:

(1) The metal is poured from a melting furnace into a ladle and there is a temperature drop to the ladle.

(2) A second temperature drop occurs between the ladle and the crucible or feeding chamber.

(3) A third drop occurs while the metal is in the crucible and the machine is picking up rotational speed.

(4) A fourth drop occurs while the metal travels from the crucible along the arm to the flask.

(5) A fifth drop occurs within the sprue and runner passages of the flask.

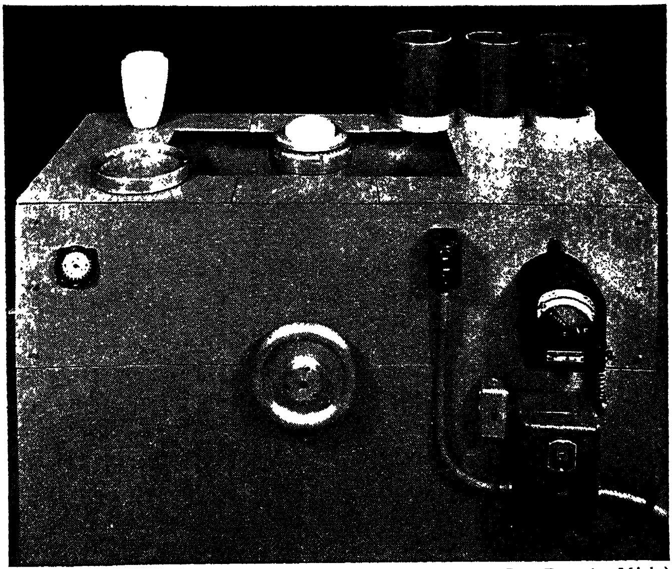
With all of these drops taking place, the actual temperature of the metal which enters the casting cavities is known only by calculation and the calculations are subject to error. Scientific experiments with pyrometers having thermocouples within the flasks have yielded data on some castings made of some alloys, but apparently not enough for general application. The original metal temperatures to be used at the furnaces are found almost altogether by trial and error. If the metals will not cast at one furnace temperature, their temperatures are raised by increments until they will. Each increment should be 50 degrees.

To get rid of some of these five temperature drop problems several stratagems are employed. Among them are:

(1) Do the original melting in an induction-heated, gas-heated or oil-heated crucible which can be handled as a ladle. This gets rid of the drop to the ladle.

(2) Apply a gas flame or other heat source to the crucible or chamber in the machine. Some casting houses maintain this heat source day and night, even when the machine is not in operation, so that the crucible never cools and the machine always is ready for use. This practice can minimize the temperature drop to the crucible.

(3) Do the original melting in an induction- or otherwise-heated crucible which either fits directly in the machine or else is mounted in the machine before the melting begins. This eliminates the ladle and crucible drops and reduces the drops to three.



(Courtesy Kerr Mfg. Co., Detroit, Mich.)

FIGURE 122. Axial centrifugal machine with rotation in the vertical plane.

Close-Coupled Crucibles. Another type of machine places the crucible out along the arm so it is "mouth-to-mouth" with the flask. Such a crucible can be inductively heated as easily as any other. In their present stages of development these machines are not so practical for multiple arm use as those which feed the metal from the centrifugal axis. But since the metal from the axis gathers velocity and strikes with some impact or flows with some erosive force when it reaches the flask, these factors also are in favor of the mouth-to-mouth technique.

The mouth-to-mouth method most nearly approaches the direct pressure machines in the reduction of casting forces to those of pressure alone. But, as was discussed in the general analysis of centrifugal casting, the use of pressure alone is not necessarily the best casting method. The inherent adaptability of centrifugal casting should not be obscured by considering only one value.

Selecting the Speed, Distance and Time. The centrifugal force increases with the square of the speed of rotation and also with the square of the distance from the centrifugal axis to the circumference of rotation. When heavy force is used, to the extent that the air can escape rapidly through the permeability of the flask, the time period over which the force must be applied in order to fill the casting cavities is low. When centrifugal machines are variable in their controls, the factors of speed, distance and time can be combined in many ways to solve casting problems. For example:

(1) *Close-coupling effect.* Increase the rpm, decrease the distance of the flask along the arm, obtain closer coupling of flask and crucible.

(2) *Alloys high in specific gravity and low in viscosity.* Reduce the distance to get close coupling, then reduce the temperatures of molten metal and of flask to the lowest practical points, increasing the rpm if necessary to permit reduction of these temperatures. Finally, reduce the rpm if practical or if desired.

(3) *Alloys high in specific heat.* Reduce the distance to obtain close coupling, reduce the rpm, increase the time.

(4) *Alloys high in specific gravity and in viscosity.* Reduce the distance to the absolute minimum, increase the rpm as little as practical, increase the time, if necessary increase the flask temperature in order to permit increasing of time, study the use of higher and of lower thermal conductivities in investment materials in accordance with the ability to gain time while obtaining the desired progressive deposition of metal.

(5) *Alloys low in specific gravity.* Increase the rpm first, then if necessary the distance, in order to gain pressure. Experiment with raising the flask temperature and reducing the distance, but increasing the time. The higher the viscosity the higher must be the pressure.

(6) *Flasks low in initial permeability.* Minimize the distance so that there will be the least "velocity shock and metal rebound" effect, the rebound of the metal being caused by the hammer blow of the entering metal followed by the gain in heat energy by the imprisoned air. Reduce the rpm and increase the time, if necessary increasing the flask temperature to do so. Correct the permeability of the investment.

(7) *Obtain desired phoresis effects.* Experiment with cluster design since the paths by which the molten metal enters the cavities are im-

portant to phoresis; the phoresis effects may otherwise be confined to the sprues instead of occurring in the castings. Ordinarily, the casting cavities should be in direct alignment with the sprue axis and the runners should have acute angles with the sprue axis so that the metal flowing through them will have the least deflection from the true direction of centrifugal force. Increase the rpm first, next the distance, and then the time, and finally the flask temperature, recombining these factors until the desired effects are obtained. Precision control of all factors is mandatory.

(8) *Eliminate undesired phoresis effects.* Generally, decrease the distance, then the rpm. But in some alloys the phoresis effects will not take place to an undesirable extent unless given plenty of time. In these instances increase the rpm, if necessary increase the distance, then work to high conductivity investment materials and low temperatures of flasks and metals to reduce the time. In any specific instance the question is whether the undesired segregation by phoresis is best prevented by a drastic reduction of centrifugal force with consequent increase of time, or by the most rapid possible increase in the rate at which the molten metal acquires too high viscosity for the phoresis to take effect, the latter being accomplished by increasing the pressure in order to be able to decrease the time. Cluster design also should be studied to eliminate long and straight lines of centrifugal force.

Oxidation vs Centrifugal Casting. Unless the molten alloys contain, or obtain, oxidizing elements, oxidation takes place only at the surface of the melt or of the casting. It is possible for molten metal, as it eddies and acquires turbulence in passing through the investment channels, to oxidize either from exposure to the atmosphere or from picking up occluded air from the investment walls, and to have the oxides mixed into the interior of the metal by the stirring action of the flow. This possibility exists with any method of casting.

The oxides always are of different specific gravity than the main body of the metal. Accordingly, under centrifugal force they will either be forced to the centrifugal circumference or else be displaced by heavier material and be segregated in an area nearest to the centrifugal axis. The latter usually happens; the oxides commonly are segregated in the sprue. But this will not happen if both force and time are not sufficient to cause and permit the oxides to segregate. Oxides can weaken runners and thus solve shrinkage problems.

This advantage of segregation of oxides in areas where they can do no damage is peculiar to centrifugal casting, although in some instances and with some alloys it can be had with other casting methods. It is a phoresis effect.

In some instances special areas must be added to the dispensable patterns in order to provide metal areas in which the oxides may gather, those areas later to be machined from the castings.

Gases and Dirts. Like oxides, gases and dirts usually have different specific gravities or densities than the main body of the metal and therefore tend to segregate as a phoresis effect of centrifugal casting. The gassed areas may be lower in weight and the dirts may be higher. Dirts often are particles eroded from the investment wall, and when this is true the best way to deal with them is to improve the investment. Since heavy dirts will go to the area of greatest centrifugal effect it commonly is wise to provide on the dispensable pattern a machinable area for their final elimination (see page 104).

Gases and dirts cannot be eliminated by centrifugal effect unless the force and time are great enough.

Radial Centrifugal. In radial centrifugal the flask either is revolved on its own axis as a centrifugal axis, similar to the centrifugal casting of tubing, or else the flasks are mounted on arms, but in such positions that the molten metal travels through the arm and makes a right angle turn into the sprue. In either case the centrifugal force is radial to the sprue axis.

This method causes oxides, gases and other light elements to concentrate heavily in the sprues and runners. It is advantageous for some castings, but generally is slower and costlier than the axial centrifugal method. Therefore the axial method usually is preferred.

In radial centrifugal, each runner is axial to the direction of centrifugal force. So considered, the same factors apply to radial centrifugal as have been discussed for axial centrifugal casting.

Cyclic Centrifugal. As was pointed out in the discussion of axial-centrifugal casting, depending upon the casting problems and conditions, there are circumstances under which high centrifugal force is wanted; other problems call for lower force. Obviously there are times when the casting house wishes it could have both. These last call for cyclic centrifugal, which may take any of these forms:

(1) The original force is low in order to expel slowly most of the air from the casting cavities; the force is increased to cause the cavities to fill completely and to keep them filled until the castings solidify.

(2) The original force is high in order to expel the air rapidly through a highly permeable investment; the force is reduced to avoid undesirable phoresis effects.

(3) The original force is low to expel the air, is raised to fill the cavities without shock, and finally is raised to its extreme limit for the machine in order to create phoresis effects and obtain gradients of alloy constituents in various parts of the castings.

Other cycles may be created in accordance with the needs of the castings. The most common method of changing the force is to change the speed of the motor, or to drive the machine through a mechanical speed changer from a constant speed motor.

Machines which change the positions of the flasks along the centrifugal arms so as to make use of change of distance to change force while the machine is in operation are not in common use but would not represent a difficult problem in machine tool design.

Cycles intended to make use of the mushy ranges of alloys, to apply one force when the highest solidification temperature elements are solidifying and another for the temperatures of lower solidification-point elements, are not known to be in general use. For some products they can cause the lower solidification-point elements to coat the casting, as for example, using a lower force and then a higher one to cause the lead in an alloy to coat a casting intended to for use as a bearing. The lower force is applied until the higher-temperature solidifying elements, such as copper, have solidified.

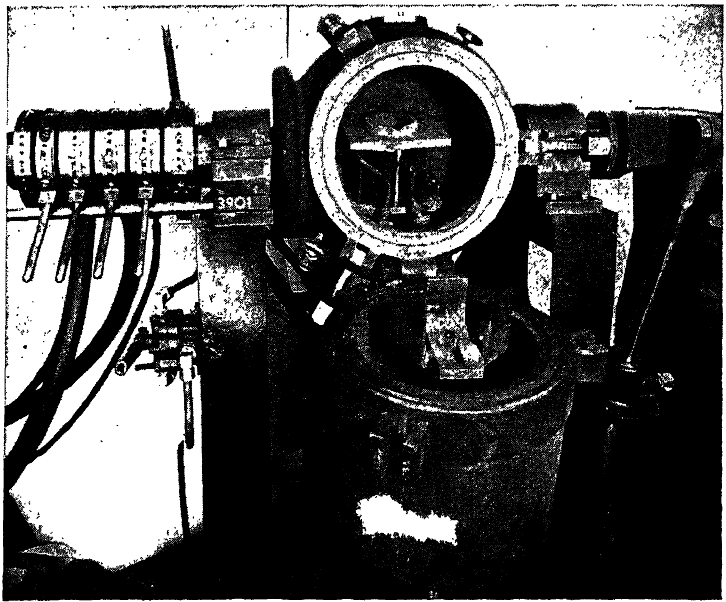
Centrifugal-Vacuum. Centrifugal force can have strange effects upon permeability (see page 325). Therefore centrifugal casting should be greatly benefited by the application of vacuum to the flask. Unfortunately, this application is difficult enough so that it seldom is practiced.

One method is to insert the bases of the flasks into chambers which are mounted on the centrifugal arms. Vacuum lines lead from these chambers to a central vacuum outlet at the centrifugal axis. These lines must move with the chambers and arms. And since it would be somewhat impractical to have a vacuum pump or vacuum tank which revolved with the axis, at some point along the revolving axis there must be a joint which has wiping contact with a stationary tube which leads to the vacuum tank. While this is a difficult problem in machine design it is by no means an impossible one. Such machines have operated successfully on a production basis.

Another method is to enclose the entire centrifugal machine (the machines rarely are large) within a bell jar having steel sides and a Lucite or other clear plastic top so that the operation is visible.

The flask is placed on the arm, the crucible full of molten metal at the axis, the bell jar is closed, heavy tank effect vacuum is applied. The machine is started only after the few seconds required to make sure that the metal going into the flask will not encounter an opposing stream of air which is escaping into the vacuum.

Vacuum-Pressure. In a vacuum-pressure system the air is evacuated from the entire flask, the metal is poured under vacuum, then air pressure as high as 500 psi is applied to the chamber. The procedure calls for placing an induction-heated crucible full of cold metal in a mechanical device within the chamber, the purpose of the device being to tilt and pour the metal after melting. The flask being within this chamber and in upward position as for gravity casting, the vacuum valves are opened, and when the vacuum is sufficiently complete the electrical current is turned on to the induction coil. Melting of the metal is rapid. The crucible automatically tilts and pours. Then the air pressure is turned on.



(Courtesy Sperry Gyroscope Corp. Inc., Great Neck, N. Y.)

FIGURE 123. Vacuum-pressure experimental casting machine open to receive flask.

Since the air pressure is equal over the entire exterior of the flask, the flask does not burst. But the air pressure can apply to the casting cavities only as the air very slowly penetrates the reverse permeability of the flask or the molten metal is pushed rapidly into the cavities. The metal therefore is pushed under 500-psi pressure into the cavities, and is compacted if the alloy is capable of being compacted by these pressures.

Controlled Atmosphere Casting. The great majority of invested flasks are melted out and heated up in reducing atmospheres, and since there can be very little convection interchange of air between the cavities and the atmosphere, the molten metal is poured into cavities in which oxidation is very slight. The surface textures obtained in precision investment could become as fine as they are in no other way. Chemical coating in multiple-coat investment techniques can still further eliminate oxidation by providing gases that have high affinity for any oxygen that may be present. But for some conditions controlled atmospheres are desired, either of gases such as hydrogen which have high affinities for oxygen and will deoxidize the melts as well as the investments, or of neutral gases such as nitrogen, helium or argon.

Controlled atmosphere casting can be done in any machine which permits the metal to be melted and poured mechanically. It is done quite often in centrifugal-vacuum machines and in vacuum-pressure machines, the usual reason being that alloys containing high percentages of zinc or of other metals which vaporize at the melting temperatures of other constituents would lose the vaporized elements if melted under vacuum.

In the customary cycle the flask and the melting equipment are placed within the vacuum chamber, the air is thoroughly evacuated, the air is replaced by the desired gas, and the melting and pouring are carried out. At this point the centrifugal method applies centrifugal pressure to the metal and the vacuum-pressure method increases the pressure of the gas to force the metal into the mold.

It is probable that no amount of vacuuming of the investment or of heating the flask in a reducing atmosphere ever gets rid of all of the occluded air in the investment. Therefore absolute elimination of oxides is not to be expected, just as no material is ever "absolutely pure." Where complete minimizing of oxides is mandatory, reducing gas atmospheres are used.

Melting Practices

The melting of alloys for precision investment casting differs from ordinary melting in only two respects. The first is that the quantities are smaller. The second is that control usually needs to be closer. With those two reservations in mind, the casting house can study the extensive literature on the subject.

Effect of Quantities. The alloying of metals, or re-alloying if the melter buys certified ingots to which he does not attempt to add anything, but from which he probably cannot help subtracting something, has the nature of a chemical process accomplished by heat. In such a process, large quantities give the advantage of general averages. There is so much heat present (in Btu's) that all sorts of liberties may be taken without raising or lowering the temperature. Ingredients can be handled with some carelessness, knowing that so long as a broad line is not overstepped their quantities will "average out." Handled in the small quantities characteristic of precision investment casting, the reverse is the case.

In small quantities the temperature has to be handled correctly or it will "go wild." The ingredients must be mixed exactly. Therefore many a man trained in a steel mill or a large foundry has "found himself lost" when he attempted precision investment casting. His measuring had to be more exact.

There also is an advantage. In the large batch the addition of a small increment of heat or of material gets lost in the general average. The batch is too big to respond. The small batch is sensitive. It will not control itself by general averages or by "fly wheel effect." But it will submit to control far more readily.

Effects of Close Control. The invested flask in position to be poured represents at least 80 per cent of the cost of the precision investment casting process in nearly all instances. That flask is a precision tool. If not poured with a controlled melt, the value of its precision will be lost. Pouring a poorly handled melt would be comparable to setting up a high-cost precision grinding machine and then running through it parts which had been so poorly machined and heat-treated that they could not be ground into precision products.

Large Quantities Sometimes Run. Continuous pouring cupolas have been set up to pour into continuously-running centrifugal casting machines which filled more than 60 flasks a minute. Such operations are highly uncommon for this industry, but can be performed. Even so the cupola was not large enough to take very much advantage of general averages. It had to be controlled closely.

Medium Quantities. Quantities large enough to warrant hot metal pot methods by which a pot full of molten alloy is always kept ready are not uncommon. The pot rarely contains as much as one ton of hot metal, and 400 pounds is the usual load. This hardly compares with the 110,000-pound lots common to steel mills in abilities to make use of general averages.

Small Quantities. The usual precision investment casting charge is melted in quantities of not over 30 pounds and is timed so that the melting is completed no sooner than the flasks are ready to be poured. Molten metal rarely gains anything by being held in its molten state, and many alloys, especially those containing chromium and carbon and other readily oxidizable materials, can be severely damaged.

Control by Test. The important matter is the alloy which gets into the castings. Therefore periodic chemanalyses of the castings should be made. If the casting house has no metallurgical laboratory of its own to make these, consulting laboratories will make them at low costs. If the analyses of the castings are highly critical to their qualities, chemanalyses of every heat should be required.

Separate chemanalyses should be made of the runners and sprues to make sure that valuable ingredients are not segregating in them. If this segregation is found, the cluster design, the type of investment, the flask temperature and the speed and pressure of casting should be investigated, in that order, to find the cure. Other tests common to the metallurgical laboratory may be made as required by the functions of the product.

If the chemanalyses show that the desired combinations of elements are present neither in the castings nor in the runners or sprues, the alloying should be corrected. It is quite common to buy certified scrap or ingots and then be forced to add readily lost elements such as carbon, chromium and zinc to make up for melting and pouring losses. The great majority of melts must be re-alloyed when melting.

If heavy inclusions of oxides or dirts are found, the investment and the investing methods are suspect. Second to be checked is the permeability of the investment, then the cluster design to make sure that undue turbulence of the alloy is not caused by some turn or twist which the liquid metal has to take en route to the casting cavities. The casting method should be checked. If some of the castings are bad but others are not, it quite commonly is found that the bad ones always are at a single position of the flask in relation to its vertical position when being poured, or in relation to the plane of rotation if cast centrifugally. The alloy ingredients and the melting method also may be guilty, but are last on the list of probabilities.

Metal that clearly is dirty, of course, never should be melted at all unless under the personal supervision of a metallurgist who is individually responsible for results. The cost of an invested flask is so high that there rarely is any "saving" in melting doubtful metals.

The usual samplings of molten metals before they are cast are highly valuable if the casting house has a laboratory available for making them. But in most instances it is better to be completely sure of ingredients and procedures than to hold the melt while the analysis is being run.

Samplings of the contents of hot metal pots should be made immediately before use. In fact, no casting house should attempt the hot metal technique unless it has a metallurgist with laboratory equipment to keep the hot metal under control.

Temperature Control. Optical pyrometers sometimes are adequate for measuring the temperatures of molten ferrous metals but almost never for nonferrous. If the temperatures of the alloys are critical, the best types of submerged thermocouple pyrometers should be used. Precision investment casting gets some of its highest values from extremely close control of molten metal temperatures.

Melting Equipment. There is no type of heat source capable of delivering high enough temperatures which is not in successful use in this field. Gas, oil, coke, and electrical heating all are in wide use. Heat adequacy plus close controllability are the sole requirements.

Induction Heaters. Induction heating is used to some extent in nearly every shop, and some houses use it exclusively. The equipment should be selected carefully. Some guide points for buying it are:

(1) Make sure that plenty of high-grade sales and application engineering is to be supplied. The average induction installation works the way its supplier makes it work.

(2) Have a setup in which the melting crucible can be located remotely from the generator. The current should be capable of being kept on while the metal is being poured. The temperature should be under control until the metal actually leaves the crucible and the induction no longer can heat it.

(3) Make sure that the load control is adjacent to the crucible and that it can be adjusted quickly. The loads are small, therefore the temperatures are sensitive.

(4) Choose a type which can handle many different sizes of crucibles, and with a capacity to handle many crucibles simultaneously. It is dele-

terious to quality control to be forced to melt more or less metal than is wanted at one time, and wasteful of the time of the entire shop not to be able to heat simultaneously many crucibles containing various alloys at different temperatures.

(5) Choose the crucible carefully. First for chemical control; if additions of carbon from the crucible may be bad for the melt, as is likely to be the case with ferrous alloys, do not use a graphite type of crucible which may add carbon. Second, for stirring effect; if stirring effect is likely to bring large bodies of oxidizable elements to the surface, select a crucible which is inductively heated and in which the stirring effect is minimal. But if the alloy contains elements of widely varying densities and the stirring effect therefore is highly valuable, use a crucible of ceramic or other type which is not inductively heated and in which the heating is applied to the metal alone and the stirring effect accordingly is greatest. The crucibles should be selected under the sales engineering advice of the equipment maker.

(6) Make sure that the power capacity is appropriate for the kind or kinds of alloys to be melted. All equipments are not completely alike, but as a general figure given for the comparisons of alloys only, the same amount of applied power should melt in the same time period, about:

100	*pounds of steel*
90	*pounds of copper*
120	*pounds of yellow brass*
50	*pounds of aluminum*
55	*pounds of magnesium*
150	*pounds of silver*

Melting Time. The melting time for any type of equipment should be highly controllable. Although some alloys can "take it," it almost never is a good idea to have some pieces or areas of metal within the crucible solid while the others are molten. Rather, the entire mass should be brought up by uniform temperature increments, the heat being applied no more rapidly than it will be conducted. Any alloy which is liable to have some elements such as zinc gasified or has elements subject to rapid oxidation must be kept under especially close control.

Differential Alloy Technique. Any large crucible may be used as a hot metal pot, or when operations are large enough outright hot metal-pot technique may be used, for securing many different alloys or modification of alloys from a single basic melt. Low carbon steel, for example, is basic to a large list of ferrous alloys. The only requirement is that the final mixture be not too sensitive to oxidation or gassing-off of its constituents.

The basic melt is heated to a temperature above its mushy range but below that wanted in the final melt. A suitable quantity of the basic melt is poured into a smaller crucible. The required amounts of additional ingredients are added to this crucible. Then the crucible is slowly brought up to a temperature at which all of the ingredients will melt, a heavy stirring action within the melt usually being desired. Finally, the crucible is brought to pouring temperature and is poured.

This is a different technique from "doping the ladle," or adding ingredients to a crucible or ladle and then pouring immediately. Doping the ladle is not good practice.

Gradual Feeding Technique. Some types of furnaces, especially some of the electric ones, have linings which will receive more damage by cooling off than the power or fuel will cost for keeping them warm. Other types require so long to start up if allowed to cool that it is more economical to keep them warm. In many such types it is common practice to keep "heels" of unpoured molten metal to aid in distributing idling heat about the linings and for higher speed in starting up.

Such furnaces may need careful progressive feeding. The molten alloy is brought above its mushy range and cold metal is added no more rapidly than the furnace can take care of it without going below the mushy range. If practical, the charge should be kept below the pouring temperature until all of it has melted, after which the entire charge should be brought up to temperature and poured.

Metallurgical Factors. The selection of alloy ingredients differs very little from ordinary foundry practice. A deoxidizer in any other casting procedure is a deoxidizer in precision investment casting, and the same statement applies to scavengers and hardeners. For further information libraries of technical literature on this subject should be consulted.

Precision Specifications. Scrap from the machine shop sometimes can be used. Scrap ends of concrete reinforcing bars, the cheapest available material, have been re-alloyed into high alloy steels in precision investment casting shops. The ability to do this depends first upon the skill of the metallurgist in the shop, and second upon the closeness of the casting specification. The savings in terms of costs per finished casting rarely are great.

When metallurgical specifications are close, as in most aircraft work, the design engineer may specify that the original melting stock be a certified material. Off heats of stainless steels and other alloys may be bought by the casting houses; the mills must find markets for these and the chemanalyses are correct for casting purposes.

The design engineer should *not* specify that the casting house shall melt a certified alloy and add nothing to that melt. Corrective additives may be mandatory.

Specifications should *not* read as they would for stock intended for automatic screw machining or for forging. The addition of chromium up to 0.50 can reduce the tendency of steels to segregate, vanadium to 0.15 is a deoxidizer and retards segregation, titanium causes steels to freeze more rapidly and thus decreases segregation. The casting house has dozens of such resources. Use of these elements in machinable stocks might reduce machinability. But machinability rarely is a criterion of casting quality.

The entire burden of alloy specification is one to be divided in accordance with ability to bear it. If the product designer has a metallurgist who knows more about cast structures as obtained by precision investment casting than does the casting house, he should specify the alloys. If the casting house has a highly capable metallurgist, he should specify. And if neither buyer not seller has a sufficiently informed man, as sometimes happens, consultants are available.

Cooling Practices

Warpage Problems. Avoidance of warpage usually is most complete when castings are allowed to cool to room temperature in the flasks. Other check points are the avoidance of too high casting pressures after the casting cavities are filled but while the castings still are plastic, study of cluster design to make sure that a heavy body is not imposing undue weight on a light section while the metal is plastic, and study of casting design as shown in Chapter 7.

Slow Cooling Techniques. When the castings should cool slowly in order to avoid stresses and resultant strains, an investment high in insulating value and a cluster design which causes the mass of metal in the flask to keep the castings in uniform thermal balance may be used. The techniques are discussed in the chapters on cluster design and on investments.

Furnace Cooling. Increasing numbers of precision investment castings are being furnace cooled as a stress-relieving operation, the technique being especially valuable when casting design includes severe undercuts or re-entrant angles (interior angles) or otherwise is liable to heavy cooling stresses. Pointers on this technique are:

(1) Any closed muffle furnace of the type usual for the stress relief of weldments may be used. The furnace atmosphere should be reducing, or at least non-oxidizing. Temperature controllability should be close.

(2) The sprue area should be large, and a wide sprue button design used. Most of the temperature differential of the castings will be established by thermal conduction along the sprue.

(3) The castings nearly always should be cooled rapidly until solid before being placed in the furnace. For rare applications the castings actually are poured by gravity while the flasks are in a hot furnace, the objective being to slow down the progressive deposition and obtain large granular structure for high ability to dampen vibrations.

(4) The investment should be high in thermal conductivity to permit rapid solidification of the castings and rapid temperature response to the furnace.

(5) The rate at which the furnace temperature is reduced is determined by trial and error but rarely is more than 100 degrees F an hour. The furnace temperature should be controlled by increments.

Sprue Control Technique. A heat source, either a hollow chamber through which molten salt circulates, or else an electrical resistance device, is arranged within a furnace or a closed chamber in such manner that the sprue button may be brought into contact with it. The heat source should be positionable to the flasks.

The flasks are allowed to cool below the solidification point, but within the chamber, which is cold. The heat source then is brought into intimate contact with the sprue button, and the door of the chamber is closed. Reduction of temperature is obtained by reducing that of the heat source. The flasks themselves may keep the closed chamber warm enough to prevent thermal shocks which would crack the investment or to prevent the flasks from cooling so rapidly as to interfere with the correct functioning of the heat source. Or in some instances the closed chamber is operated as a furnace and is kept at constant temperature gradients.

Salt Bath Cooling. The flask is cooled below the solidification range, then is immersed in a molten salt bath for controlled rate of cooling. Care must be taken that, if the flask contains any paper lining or other carbonaceous material, the salt is not of a type which will have explosive reactions with this material. The makers of heat-treating salts should be consulted before this technique is attempted.

Mild Water Chilling. Where rapid deposition of cast metal is wanted, or rapid cooling after solidification, this technique may be used.

A bath of circulating water is arranged with a wire screen or a piece of perforated sheet metal of strength sufficient to hold the flasks being positioned a predetermined distance below the surface of the water. The screen usually is about 0.25 inch below the surface. Flow of water should be constant, but not rapid enough to cause turbulence.

Immediately after casting, immediately after the sprue tip has frozen, or after the castings have had time to solidify (dependent upon the results desired), the flasks are placed upon this screen with the sprue tips upward. There will be an instant evolution of steam; therefore the operator should be well shielded.

The water instantly begins to cool the flask, and also may pulverize the portion of the investment which is contacted. If enough of the investment is fractured to expose the castings to the water, either this condition should be determined to be desirable or else a less heat-sensitive investment material should be used.

A lower depth of water above the screen also may help. Control of the water temperature also is useful for this purpose, the water sometimes being used at room temperature, sometimes at colder or "well or line" temperature, but sometimes being up to 200 degrees F.

As the flask cools slightly the steam tends to penetrate the investment permeability. The first moisture to reach the castings undoubtedly is high temperature steam. Cooling is somewhat gentle and progressive, but is more rapid than cooling in air. This type of cooling often results in a finer grain structure in the castings. It also is used when the runners are parallel to the flask bottom and it is desired to make certain that they solidify before the castings do.

Sprue Plunging. The mild water chilling technique sometimes is increased in speed by placing the flask with sprue downward. This rarely is done before the castings have solidified. It may crack and shatter the sprue, but it makes better use of the high thermal conductivity of the metal and it has a greater effect in breaking up the investment for easy removal from the cluster.

Flask Plunging. After the castings have had time to solidify, the entire flask may be plunged into cold water. The result usually is pulverizing of the investment and rapid cooling of the castings.

Nonferrous and some of the ferrous alloys may be greatly benefited by this treatment. Other alloys will be shattered.

The decision as to whether or not to use the method cannot be based solely upon the ability of the alloy to be quenched in water. As the flask shatters, one narrow area of a casting may be exposed to water while other areas are insulated by investment. This usually has more of a stressing effect than if the cooling were uniform over the surface of the piece.

The temperature at which the plunging is done is important. No quench-hardenable material should be plunged from a temperature higher than that at which it would be quenched.

If rupturing of the investment is the sole reason for the plunging, this may be done at any temperature at which the water which penetrates the permeability will form high pressure steam. These temperatures, ranging generally from 300 to 400 degrees F, rarely are injurious to metals. And experiment may find that the destruction of the investment actually is more complete at the lower temperature.

Heat-Treatment Options. The rates of cooling of the castings within the flasks are subject to close control, and it is practical to lower and then raise these temperatures or to "jockey them across the critical ranges" for heat-treatment effects. The values for heat-treatment can be high, especially in alloys which would be placed in insulating materials before being heat-treated if removed from the investments.

The heat-treater also has the option of removing the investments and the scrap and heat-treating the castings as he would any other finished or semifinished materials. This method often is more economical.

In the hands of the heat-treater the individual castings are "just some more metal pieces to be treated." Chemanalyses of individual heats may be needed for very close results. But when precision investment castings of SAE analyses numbers 1015, 1095, 3415, 4130, 4340, 4640 and 6150 were heat-treated by standard procedures appropriate for them, the procedures being the same as those used for wrought and forged products, the strengths and hardnesses obtained in the castings were directly comparable to those obtained in bar stock and forgings.

Precision investment casting is a highly controllable process. When heat-treat abilities are wanted in the castings the process needs only to be controlled accordingly.

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